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ABSTRACT

This module is designed to give the learner an understanding of the nature of light and how its properties are used in the design of spectrophotometers. Problems promote the use of spectrophotometers in qualitative analysis, the optical elements used in a monochromator, and the physical properties of the prism and the diffraction grating. Other learning tasks promote the understanding of the characteristics of light and the electromagnetic spectrum. (Author/SA)

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TECH PHYSICS

THE SPECTROPHOTOMETER II

A MODULE ON THE SPECTRAL PROPERTIES OF LIGHT

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SE 029 876

PREFACE TO THE STUDENT

The Tech Physics modules provide a program in experimental physics primarily for the technical student. The methods of presention therefore differ considerably from that of standard materials. This preface highlights some of the features of the module in order that you may use it most effectively and efficiently.

THE TITLE: Each Tech Physics module is centered on a particular operating device or system. These systems are either familiar to you or you may meet them in a later work situation. Usually the operation of the device will depend on some general area of physics that is relevant to the technology involved. This area of physics is listed in a secondary title for the module.

THE INTRODUCTION: A brief introduction explains why we have chosen this particular device and what principles of physics we expect you to learn from it. Several examples are given to show why these principles are important to you and where else you may encounter them.

Objectives are then given for the module. These include a general discussion of the goals of the module and specific things you should be able to do to demonstrate that you have achieved these goals. After each objective is listed the pages in the text where it is discussed, and Problems and Questions that you can do to test whether you have achieved the objective.

Pre-requisites to the module indicate the kinds of skills and knowledge that you will use in the module, but will not be discussed. The lack of one or two of these pre-requisites should not prevent you from doing the module since they can be learned as you go along. However, any more than that would suggest doing a module whose pre-requisites you have or learning the missing ones.

THE ARRANGEMENT OF MATERIAL: The module is divided into three separate sections of different colors. Each of these sections is designed to be completed in about one week's time.

The first week is usually devoted to familiarizing you with the device, the instrumentation you will use to measure its performance, and the terms that describe its characteristics. Often this will mean learning how to use a new measuring instrument or transducer.

The second week generally focuses on an experiment involving some specific behavior of the device. The laboratory instructions are quite explicit as to experimental procedures, taking of data, graphing of data and data analysis. This is to familiarize you with the experimental methods involved with this area of physics.

The third week generally will involve doing some additional studies of the device, utilizing the instrumentation learned in the first week and the methods of data taking and analysis learned in the second week.

THE ACTIVITIES OF A WEEK: Since this is primarily a program in experimental physics, the material emphasizes the experimental activities. A short introduction should orient you to the experiment you will do, and to the important physics principles or skills that should come out of it. This is immediately followed by the experiment itself, including the set-up and data taking procedures.

Often the principal experiment is preceded by some simple ones. These are included to give you a feel for what you will be doing in the main experiment. They generally can be done quite quickly and do not require extensive data taking. The principal experiment, however, should be done carefully to obtain good data since the remainder of the material will discuss these results.

Once your experimental work has been completed and all of your data taken, you may leave the laboratory. The remainder of the material is devoted to helping you graph and analyze your data and to explaining the physics involved. This work can be done either as homework or in class with your instructor.

In reading the material be sure to keep in mind the module objectives. Although this material generally goes beyond what is needed to achieve the objectives, your test at the end of the module will be on the module objectives.

Finally, the module has been designed to provide you with an understanding of physics that will be of use to you. Within the text you will find conversion tables, methods for calibrating transducers, explanations of physical terms, comparisons of ways to measure a physical parameter, and so on. These could be useful to you in a later work situation and you may want to tear them out and keep them as permanent reference material.

I hope that the material in these Tech Physics modules will provide you with the skills of experimental science as well as insight into the physical principles underlying your technical field.

January 1973

TERC

Cambridge, Massachusetts

John W. McWane
Project Director

THE SPECTROPHOTOMETER

An Introduction

WHY STUDY SPECTROPHOTOMETERS?

The physics involved has many applications. In order to really understand how a spectrophotometer works and is used, you will have to learn about light and how it is produced, measured, controlled and detected, and about color. The principles involved come up every day in applications far from spectrophotometers. For example, the light that we see with our eyes, *visible light*, is only a small part of a more general kind of radiation called *electromagnetic radiation*. Other types of radiation include radio waves, microwaves, x-rays, gamma rays, infrared and ultraviolet radiation. The spectrophotometer you will use here utilizes not only visible light but also the latter two types of electromagnetic radiation, infrared and ultraviolet, that your cannot *see*. Other instruments, called more generally spectrometers, exist for studying the other types of electromagnetic radiation, (gamma ray spectrometers, x-ray spectrometers, etc.), and these other spectrometers have most of the same basic components that you will study here. Thus, many of the principles that you will learn in your study of the spectrophotometer are useful considerably beyond this particular application.

MEASURING LIGHT ABSORPTION. . .

In the first part of the module you will put together a very simple spectrophotometer using your eye as the detector of light. You will see how various materials absorb visible light differently, and that two materials that may look alike to the eye have quite different light transmission (or absorption) properties. These so-called *transmission spectra* are central to the way in which spectrophotometers are used in analysis.

THE DISPERSION OF LIGHT. . .

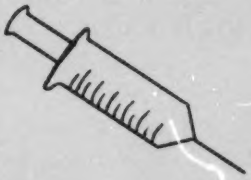
In the second part of the module you will study components used to separate or disperse white light into its various component colors. Prisms and gratings are the components, called *dispersive elements*, that will be studied. These elements depend on different optical principles and therefore act differently. You will learn how to describe and explain these principles and will observe the operation of the dispersive elements and their differences.

SPECTROPHOTOMETER ANALYSIS. . .

Finally you will use the ideas of the first two parts to assemble a functioning spectrophotometer system, and use it to measure quite accurately the transmission spectrum of a *didymium* (di-dim'-ē-um) glass filter. This will introduce you to the techniques of spectrophotometric analysis and at the same time show you how spectrophotometers are calibrated. Didiymium is a mixture of rare earths whose transmission spectrum is well known. It is commonly used for spectrophotometer calibration.

Spectrophotometers are widely used. The following areas provide examples of the widespread application of spectrophotometers:

Medicine: Spectrophotometers are routinely used to analyze body fluids to help spot body malfunctions and disease before they become serious. For example, a standard test for diabetes involves using a spectrophotometer to measure the sugar level in urine.



Pollution Control: Widespread use of powerful insecticides and pesticides creates an increasing threat of poisoning ourselves and our water. Scientists use spectrophotometers to find trace amounts of these toxic compounds before they cause harm.

Beer Production: Brewers use spectrophotometers instead of tasters to monitor the color and flavor of beer coming off the production line.

Astronomy: Before the gas helium had ever been found on earth, spectrophotometers had located it on the sun. Spectrophotometers have also been essential in determining the speed, size and age of thousands of stars.

Law Enforcement: Police and coroners' laboratories use spectrophotometers to identify poisons which are difficult or impossible to tag any other way. Narcotics and sleeping pills are examples. Race tracks run routine tests with spectrophotometers to check whether horses have been drugged.

MODULE OBJECTIVES

The general goal of this module is to give you an understanding of the nature of light, and how its properties are used in the design and operation of spectrophotometers.

This involves a knowledge of:

* The wave description of light and its application to infrared, visible and ultraviolet radiation.
* The terms used to describe light colors (wavelengths), and the graphs used to display the transmission of these colors by various materials (transmission spectra).
* The devices used to disperse light into its component wavelengths (prisms, gratings) and the physical processes (refraction, diffraction) on which each depends.
* The operating principles of spectrophotometers including the purpose of each of its basic components, the methods used for calibration, and the procedures for making qualitative analysis.

At the end of this module you should be able to demonstrate your understanding of its objectives by doing the following:

	Pages Where Discussed	Problems and Questions
1. Explain the use of spectrophotometers in qualitative analysis and the physical principles on which this is based.	6 12-18 64-67	Page 64 Q - 1,2,3
2. Describe the basic components of spectrophotometers (source, monochromator, sample, detector, display) and explain the purpose and behavior of each using proper terms.	7-11 68-70 74-75	Page 64 Q - 4 Page 65 P - 1,2

	Pages Where Discussed	Problems and Questions
3. Describe the optical elements used in the monochromator (slits, lenses, flat and spherical mirrors, dispersive elements) and explain the purpose and behavior of each element using proper terms.	23 38-40 49-53	Page 77 Q - 1-6 P - 1,5
4. Explain the characteristics of two dispersive elements, the prism and the diffraction grating, including: -the physical properties on which each depends, -the wavelength dependence of dispersion, -the range of usefulness in spectrophotometers.	19-26 37 41-44	Page 46 Q - 7-10 Page 47 Q - 11-15 Page 48 P - 11,12,13
5. Draw a diagram of the electromagnetic spectrum showing the range of wavelengths for the infrared, visible and ultraviolet and describe the properties of each type of radiation.	27-28 35-36	Page 46 Q - 5,6 Page 47 P - 4
6. Describe why four important characteristics of light (reflection, refraction, interference and diffraction) are consistent with a wave model for light.	27-30	Page 47 P - 5
7. Convert among the various units that describe the colors of light (nanometers, Angstroms, millimicrons, Hz).	31-35	Page 47 P - 7,8 Page 48 P - 9,10
8. Assemble the student spectrophotometer using: a) either a prism or a diffraction grating to break the light into colors and, b) either mirrors or lenses to focus the light.	9-10 13,21,24 54-58 71-73	Page 77 P - 4

		Pages Where Discussed	Problems and Questions
9.	Calibrate the student spectrophotometer using a didymium filter and its transmission spectrum.	62-63	Page 77 Q - 7
10.	Operate the spectrophotometer to obtain the transmission spectrum of a sample of unknown material.	11,22 23,59	
11.	Graph the spectrophotometer data to obtain the transmission spectrum of the unknown sample.	12 60-1	
12.	Identify the composition of the unknown by comparing its transmission spectrum to spectra furnished by the instructor.	14-15	Page 77 P - 2-4,6

PREREQUISITES:

Before beginning this module you should already have the following skills, since they will be used but not described in the module:

1. graphing data on linear graph paper,
2. using scientific notation,
3. solving simple algebraic equations,
4. reading meters,
5. aligning simple optical components (lenses, mirrors, slits).

If you are unsure whether you have these prerequisites, ask your instructor to give you a prerequisites test.

If you find you do not have a certain prerequisite ask your instructor to give you material to help you learn the needed skill; or have someone help you learn it as you need it in the module.

MEASURING LIGHT ABSORPTION

WHAT IS A SPECTROPHOTOMETER?

A spectrophotometer answers questions about how light is affected by various substances. It is important to realize that light can be reflected from, absorbed by, or transmitted through any given sample; and that the fraction of the light reflected, absorbed, or transmitted *depends on the color* of the light. A spectrophotometer is a laboratory instrument for measuring precisely these fractions reflected, absorbed, or transmitted for any color within a large range.

The importance of spectrophotometers can only be appreciated when you realize that different chemical substances have very clear and unique patterns of absorbtion and reflection. These patterns are like fingerprints since they can be used for identification. Spectrophotometers can provide a quick, simple means of detecting and measuring even small amounts of chemicals. Thus, they have found wide use in scientific research and industry.

White light from an incadescent light bulb is actually a mixture of many colors of light. When white light is separated into its component colors the result is called a *spectrum*. This is where the "spectro" part of the name comes from. "Photometer" simply means light meter or light measuring device. Thus, a spectrophotometer is a device which measures the light spectrum of something. To be exact, a spectrophotometer measures the amount of each color of light which is absorbed by a sample. Since different substances absorb characteristic amounts of different colors, you can find out *what* substances are present in a sample of material - *qualitative analysis* - and *how much* - *quantitative analysis* -- just by passing light through it.

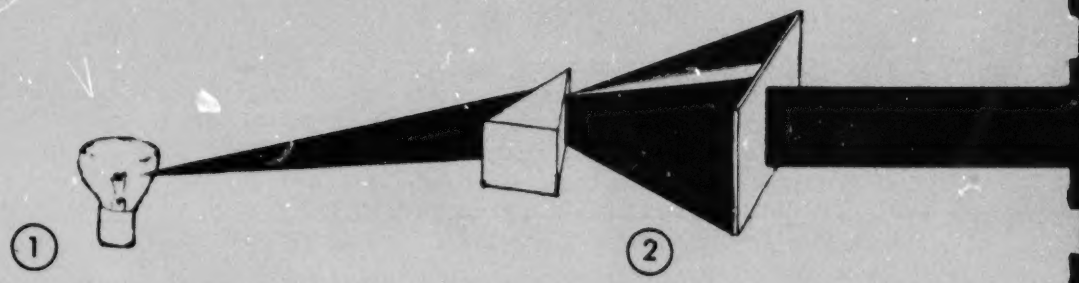
There are five major parts to all spectrophotometers:

1. The *light source*.
2. A *monochromator* which selects one color from the source.
3. A *sample* where part of the light is absorbed.
4. A *detector* of light which converts the light to an electrical signal.
5. An *amplifier and display unit* which reports the light level.

The drawings on the next two pages show each of these components in the student spectrophotometer that you will use.

SPECTROPHOTOMETER

SCHEMATIC:



NAME:

SOURCE **MONOCHROMATOR**

FUNCTION:

An ordinary bulb makes white light. . . . . .

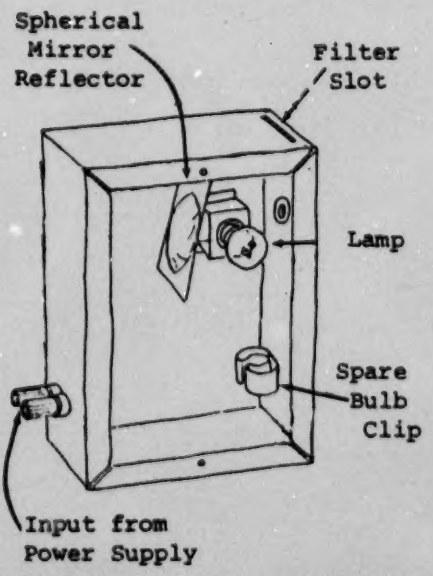
which is spread into a spectrum of colors. A slit passes one color of light. . . . . .

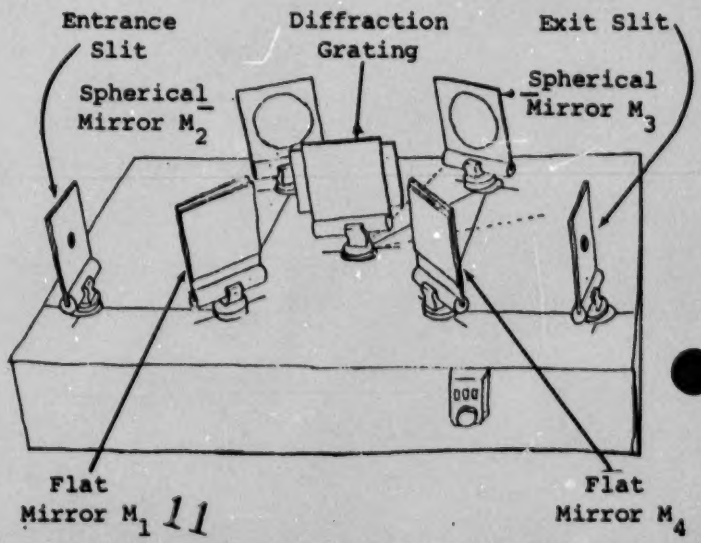
DETAILS:

Most light sources produce light of many colors. An ordinary incandescent light bulb is satisfactory for visible colors, but special bulbs are needed if measurements are to be extended far beyond the blue or red ends of the visible spectrum.

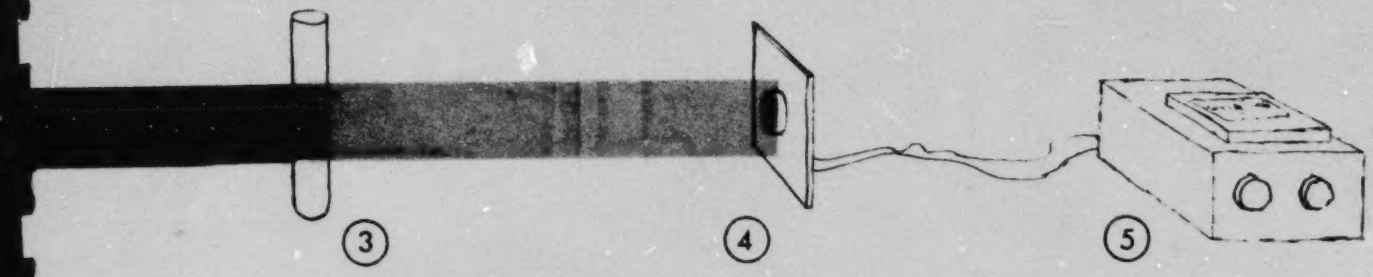
With a monochromator you can pick one color out of the many produced in the source. This is done by breaking the light into its spectrum with a prism or diffraction grating. Then only one color from the spectrum is allowed to exit through the slit. A dial permits you to change the color of light coming out over a wide range.

REAL LIFE: *This bottom line shows parts of the student spectrophotometer that you will be using in the laboratory.*





COMPONENTS



SAMPLE

which strikes a sample. A portion of light passes through the sample

Every element or compound will absorb only certain colors. The pattern of absorbtion is unique to that compound and serves to identify it. Thus, if a certain compound is present in a sample of material being analyzed by a spectrophotometer, its unique pattern of absorption will show up and the operator will know that it is there.

DETECTOR

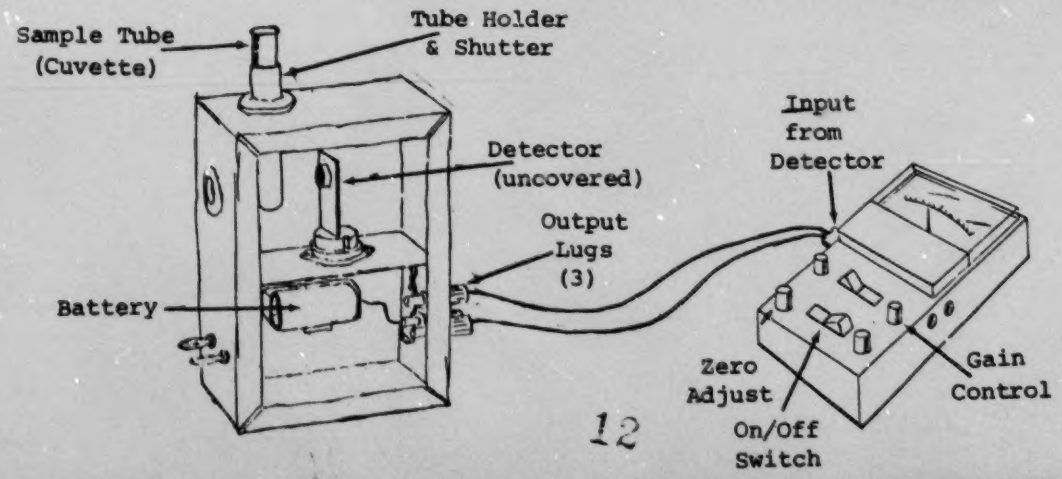
and strikes the detector. The amount of light striking the detector. . . .

A detector is a device which generates an electrical signal when light falls on it. The size of the signal is proportional to the amount of light. Thus, a bright light indicates low absorption and will cause a large electrical signal. Several types of detectors may be used, depending on the range of colors and brightness desired.

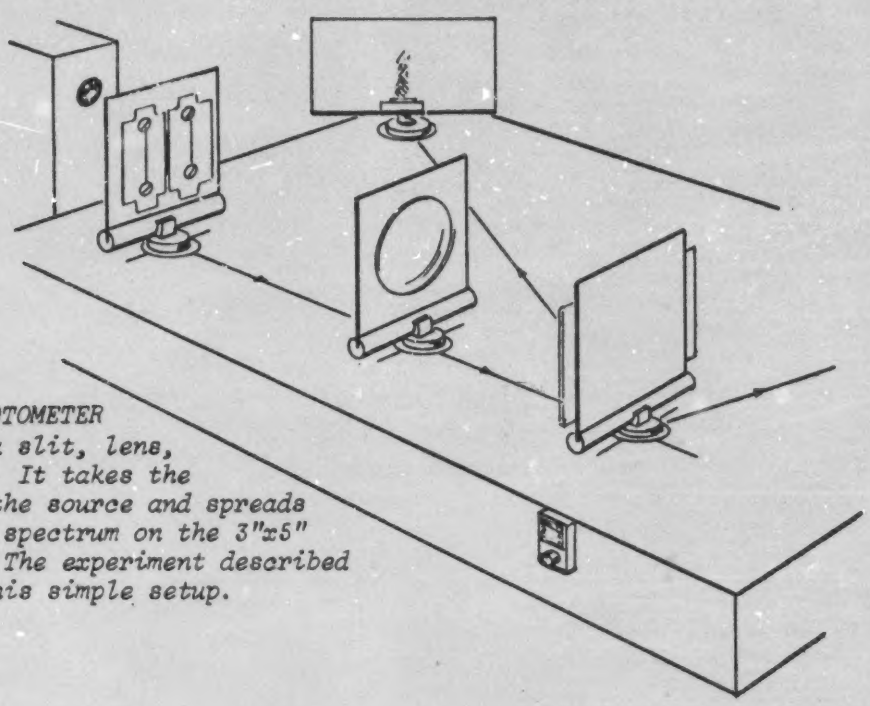
DISPLAY

is electronically measured and displayed on a meter.

The signal from the detector is rarely large enough to move a meter needle, so an electrical amplifier similar to those in radios is needed. Actually, a meter is only the simplest form of display. Commercial units often automatically graph the absorption on a chart recorder as the color is changed.



A SIMPLE SPECTROPHOTOMETER



A SPECTROPHOTOMETER using only a slit, lens, and grating. It takes the light from the source and spreads it into the spectrum on the 3"x5" card shown. The experiment described here uses this simple setup.

INTRODUCTION

YOUR EYE AS THE DETECTOR

We can make a simple spectrophotometer in the lab. For a first attempt we will make one which illustrates the principles but is so simple that it is too inaccurate for practical use. After we learn more about light and optics, we will assemble a more practical and accurate spectrophotometer.

The first simplification we will make is to use your eye in place of the detector and meter. You will look at a spectrum and estimate how much of each different color is in the spectrum. With practice, you will be surprised how well you can estimate.

Follow the steps on the next 4 pages to obtain your data.

CAUTION--Read this first!

THREE THINGS TO WATCH OUT FOR IN THE LAB:

1. Front surface mirrors. Common mirrors have silver behind glass. This protects the silver and makes long-lasting mirrors. BUT, the mirrors in this lab have silver in front of the glass to improve their quality. It is very easy to scratch off the thin silver layer. So don't put them face down, don't touch the mirror surface, and if you see that a mirror is dirty don't try to clean it. Cleaning will badly scratch the surface.

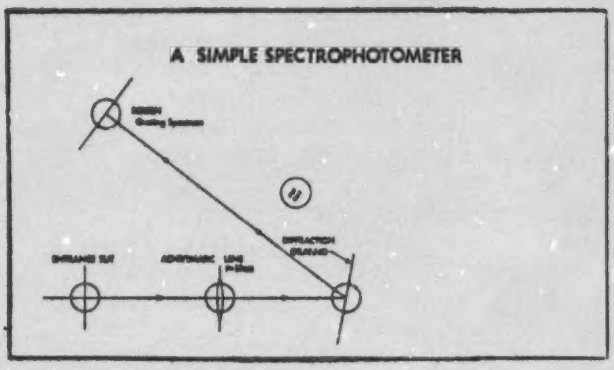
2. Diffraction grating. This also has a delicate front surface, just like the mirrors. Thus, the same precautions apply to gratings as to mirrors, but they are even more important because some gratings are very expensive.

3. General care. The experiment uses delicate scientific equipment -- treat it all with care. The prisms can chip and the mirrors can break. The lamp and detector are both fragile and can break or lose alignment. Please be careful.

PROCEDURE

1. SETTING UP A GRATING SPECTROPHOTOMETER.

Obtain the paper template titled A SIMPLE SPECTROPHOTOMETER and tape it securely to the base, centered on the center hole. Place the components on the base as shown in the sketch and the plan at the right. If you do this, you should see the colors of the rainbow making a spectrum on the white 3" x 5" card. You may have to make some adjustments to make it work best. This procedure is called *alignment*.



THE LAYOUT of the spectrophotometer used as seen from above. When setting up the experiment, it is important to use approximately the angles and distances shown.

The layout plan provided in the laboratory is a guide only. Do not be upset if proper alignment requires the various elements to be off their printed circles. The manufacturing techniques are not very precise so every spectrophtometer is slightly different.

2. ALIGNMENT.

Every time you set up an optical system you have to fuss with it to make it work well. The general idea is to start at the source and make the maximum amount of light go squarely through the center of each component. *Follow the checklist below* for the details of aligning this experiment.

AN ALIGNMENT CHECKLIST

1) We want as much light as possible to come through the first slit, so move the slit around so that the brightest and *smallest* possible line of light hits the center of the slit.

2) We also want the lens to focus the maximum possible light. Find the beam of light coming from the slit by letting it hit another 3"x5" card you hold. (See illustration on the next page.) Make sure that the lens is in the center of this beam. If it is not, slide it sideways into the center, but do not move it any closer to the slit.

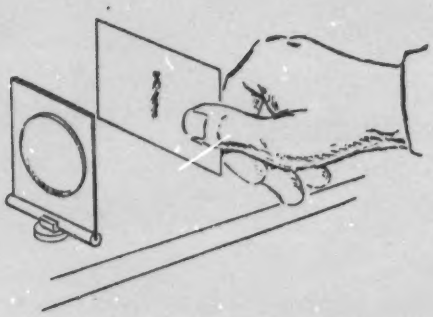
3) Slide the grating so that it also is in the center of the light beam, but do not move it any closer to the lens.

4) Now, turn the grating so that a rainbow of colors, called the *spectrum*, falls on the white card. All the spectrum should be on the card, with the blue on the left.

3. FOLLOWING THE LIGHT PATH.

Before using your spectrophotometer, be sure you have a clear idea of where the light is going. The light starts in the source box. It then goes through the slit, the lens, and strikes the grating. The grating reflects the light in several directions. One beam of light is broken into a spectrum as it goes to the white card.

To get another view of the light path, *light some incense, place it in the box and close the cover.* The smoke from the incense will let you "see" the paths of light going through the system. Have you maximized the light transmitted by each component?



AN EASY WAY to find the light beam using a 3" x 5" card. The beam can be followed from source to card using this trick. Be sure that the maximum amount of light is transmitted by each component.

4. USING THE GRATING SPECTROPHOTOMETER.

Now that we have an instrument, what can we do with it? The simplest use is to look at the effects of colored filters on the spectrum. With your equipment you should find a pack of many plastic filters. *Find out the effect of various filters* on light by placing them in the light path near the slit. You will find that the deeper or darker filters have a more noticable effect.

5. ABSORPTION AND TRANSMISSION.

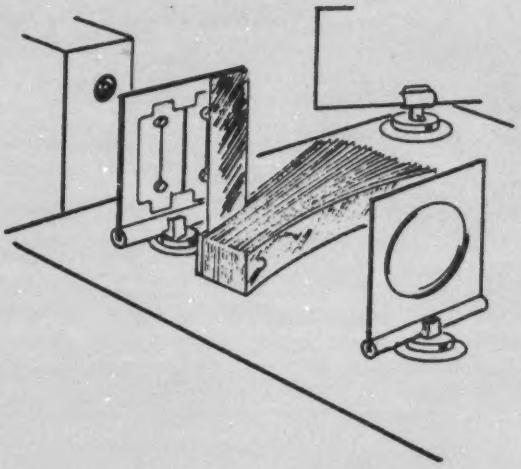
You will also find a pale blue glass filter called a *didymium filter*. This filter fits into a slot in the source box. See what it does to the spectrum.

Notice that the didymium filter removes almost all of the yellow from the spectrum. We say that this filter *absorbs* yellow. On the other hand, the filter does almost nothing to most of the blue. In other words, it *transmits* in the blue. A spectrophotometer is used to determine exactly how much of each color is absorbed or transmitted.

6. A CAREFUL STUDY.

Let us choose several filters and do the best job we can to determine which colors each transmits. Repeat the measurements on the next page for each of the following filters:

1) Number 821, a red filter;
2) Number 809, a yellow filter;
3) Number 871, a green filter;
4) Number 856, a blue filter;
5) Number 849, a pale blue filter that looks almost like didymium;
6) The didymium filter;
7) Number 890, a gray filter.



AN EASY WAY to place a filter in the light beam. Be sure <u>all</u> the light goes through the filter and none can get around it.

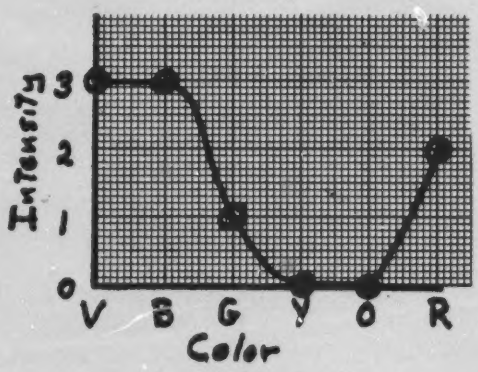
Now use your eye to estimate the spectrum passed by each filter. Judge the amount of light at each color using a scale with four values. You should be able to estimate whether the light of each color coming through the filter is:

3-*very bright* -- as bright as with no filter: no light is absorbed by the filter;

2-*bright* -- most of the light gets through the filter: some of the light is absorbed;

1-*dim* -- most of the light is stopped by the filter: only some is transmitted;

0-*dark* -- all of the light is stopped by the filter: none is transmitted.



A SPECTRUM showing the graph described and points corresponding to a filter in the pack provided.

Record your results on a grid like the example shown opposite. Use the graph paper provided at the end of this section for your data.

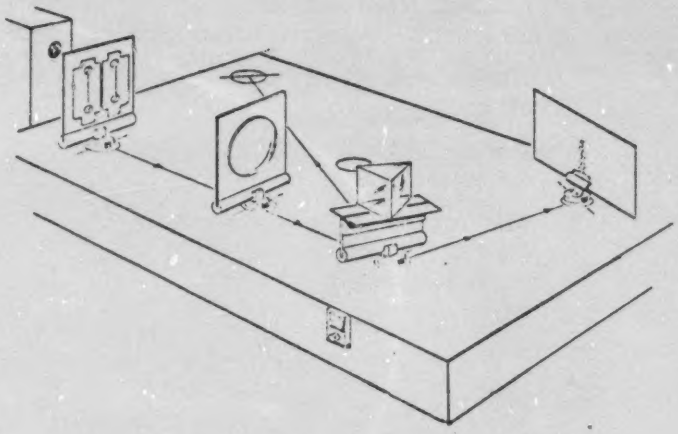
By connecting the O's we make what is called a *transmission spectrum*; a graph of the amount of light transmitted for each color.

Draw a transmission spectrum for each of the filters.

Explore the transmission spectra of some of the other filters given. See if you can find the filter with the spectrum on the previous page.

7. A PRISM SPECTROPHOTOMETER.

Now set up a different spectrophotometer which uses a prism to break up the light instead of a grating. Place the components as shown in the sketch at the right. Then run through the alignment checklist of steps 2 and 3. To get the best spectrum rotate the prism so that the spectrum is as far to the right on the card as it will go.

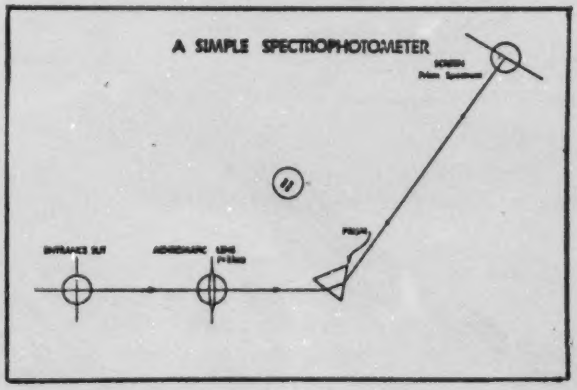


A PRISM SPECTROPHOTOMETER. This is a sketch of a spectrophotometer using a prism to break up the light. It is similar in many respects to the grating spectrophotometer.

What differences do you notice between the spectrum made here by a prism and the spectrum made before by a grating? For convenience in comparing, the distance from the prism to the 3" x 5" card is the same as the distance was from the grating to the 3" x 5" card. Likewise, the distance from lens to prism equals the distance we had from lens to grating. Essentially, the grating has been replaced by a prism with no other changes.

8. USING THE PRISM SPECTROPHOTOMETER.

To get a better idea of the difference between the prism and grating, *repeat your measurement on the didymium filter* with this spectrophotometer. Estimate the transmission of each of the colors for the didymium filter. Connect the points to make the didymium transmission spectrum.



THE LAYOUT of the prism spectrophotometer.

ANALYSIS OF YOUR TRANSMISSION SPECTRA

WHAT HAVE YOU MEASURED?

Let us think about the transmission spectra you how have: several using the grating and one repeating the didymium filter using the prism. To help you start thinking about your measurements, use your spectra to answer the questions below. Place the letter of the correct answer in the space provided on the left.

_____ 1. To the eye, the didymium and pale blue filters seem to be (A) exactly the same, (B) quite similar but different, (C) quite different.

_____ 2. Judging by your spectra, these two blue filters seem to be (A) exactly the same, (B) quite similar but different, (C) quite different.

_____ 3. If two filters look the same, they must transmit the same colors. (T) True, or (F) false?

_____ 4. Which of the following colors was *absorbed* most by the didymium filter? (1) Red, (2) orange, (3) yellow, (4) green, or (5) blue?

_____ 5. What color was *transmitted* best by your *yellow* filter? (1) Yellow, (2) green, (3) blue, or (4) violet?

_____ 6. What color was *absorbed* most by your *yellow* filter? (1) Red, (2) orange, (3) yellow, (4) green, or (5) blue?

_____ 7. Which of the following colors was *absorbed* most by the blue filter, number 856? (1) Red, (2) yellow, (3) green, (4) blue, or (5) violet?

_____ 8. From this information, what color do you guess can be removed from white light to make blue light? (1) Red, (2) yellow, (3) green, (4) blue, or (5) violet?

_____ 9. From the facts above, can you guess what color would be transmitted best by a *yellow* filter? (1) Red, (2) orange, (3) yellow, (4) green, or (5) blue? (If you are in doubt, try it.)

_____ 10. Guess which color would be *transmitted* most by a green filter. (1) Red, (2) orange, (3) yellow, (4) green, or (5) blue?

_____ 11. Compared to the grating, the prism spreads the colors out more. (T) True, or (F) false?

_____ 12. Compared to the grating, the prism is brighter? (T) True, or (F) false?

_____ 13. The two didymium transmission spectra are the same. (T) True, or (F) false?

_____ 14. A major difference between the grating and the prism is (A) None. (B) The prism absorbs more light. (C) The grating spreads out the colors more. (D) The prism focuses the light better. (E) The grating absorbs some wavelengths.

_____ 15. Is it possible to find two filters that look alike that would result in the same graph in this experiment?

_____ 16. If two filters look different must there actually be a difference in their spectra?

Pretend you forgot to label your eight graphs. Can you figure out the color of each filter by looking at the graphs? Try it.

HOW GOOD IS YOUR SPECTROPHOTOMETER?

If you can, compare your spectra with a friend's. You will probably find that you generally agree. Your spectra have roughly the same ups and downs as his. However, if you compare them carefully, you will find differences in details.

You probably disagree with some of his dots. Your friend's judgement about the amount of light at any color was probably different from yours at least some of the time. How many times did you disagree? Who was right?

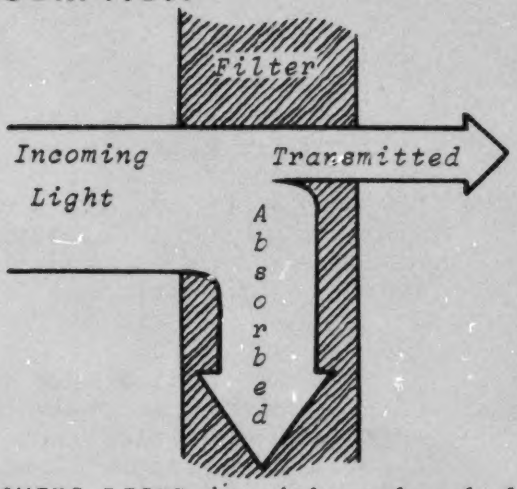
These disagreements are probably the fault of the instrument; they are expected even from the most careful experimenters. We clearly need better instruments. The remainder of this module is concerned with understanding and building a better spectrophotometer.

TRANSMISSION & ABSORPTION

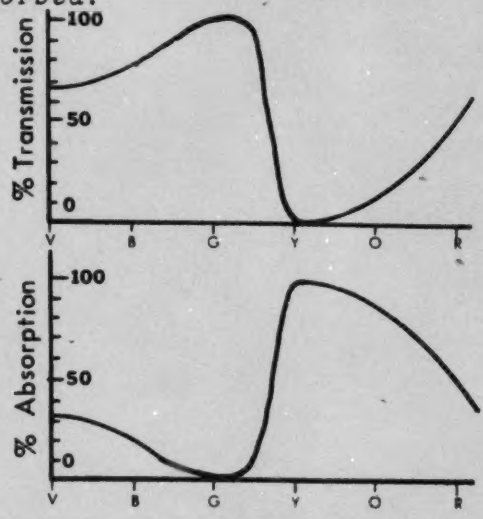
It is important to realize that incoming light is either absorbed or transmitted. The fraction transmitted is often expressed as the *percent transmission*. Likewise, the fraction absorbed is often expressed as the *percent absorption*. The sum of these two percentages must be 100%.

The percent of incoming light transmitted depends on the color of the light. As we have seen, a red filter will transmit a large percentage of the red light falling on it. On the other hand, it will absorb large percentages of colors far away from red in the spectrum. A graph of percent transmission for each color, similiar to the graphs we have made, is called a *transmission spectrum*. A graph of percent absorption for the various colors is called an *absorption spectrum*.

These two graphs have an interesting relationship. At each color the percentages of absorption and transmission add to 100%. Thus, for colors like green in the sketch at the right, where the transmission is large, the absorption must be small. Thus, there are peaks on one graph where there are valleys on the other.



INCOMING LIGHT is either absorbed or transmitted. Each different color may have a different fraction absorbed.



COMPLEMENTARY GRAPHS of % absorption and transmission for the same substance.

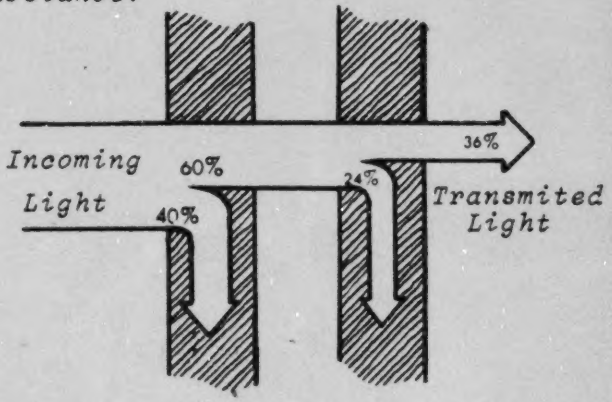
WHAT HAPPENS WITH TWO FILTERS?

You can now understand the effect of two filters. For example, suppose each transmitts 60%. The second filter only "sees" 60% of the incoming light. Only 60% of this 60% gets through the second filter. Thus, 36% is transmitted by the two filters together. In general, the fractions transmitted by each filter are multiplied to obtain the net fraction transmitted. In this case the calculation was:

$$t_1 \times t_2 = t,$$

or

$$.60 \times .60 = .36.$$



TWO FILTERS with 60% transmission each. The second transmits 60% of 60% of the incoming light, that is 36%.

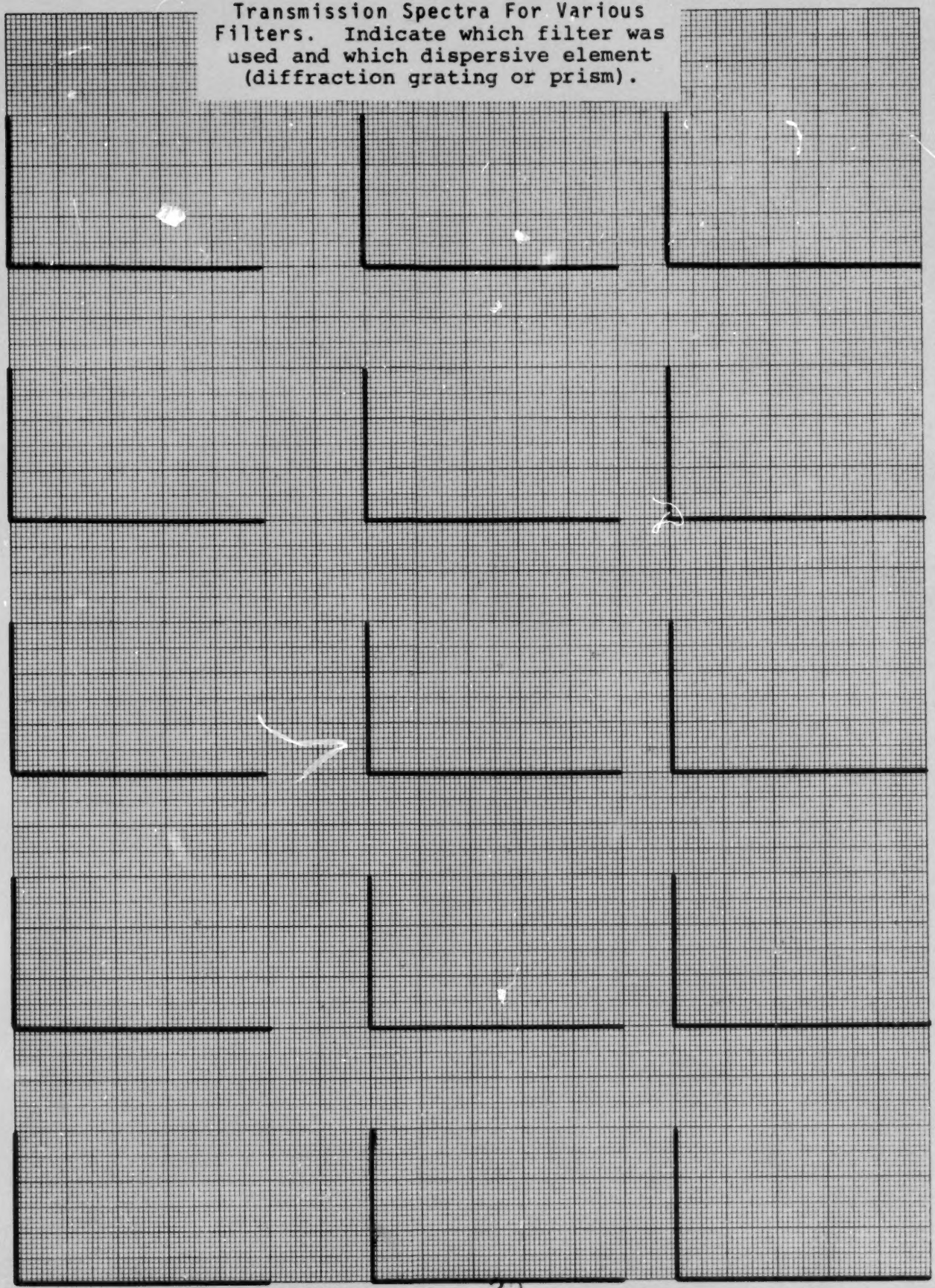
LOOKING AHEAD

We begin our deeper study of the spectrophotometer by going right to its heart -- *the dispersive element*. It is the dispersive element (either a prism or grating) which breaks white light into its spectrum. The quality of a spectrophotometer is largely determined by the ability of the dispersive element to separate out the various colors. The two most common types of dispersive element -- the prism and reflection grating -- are in the next section.

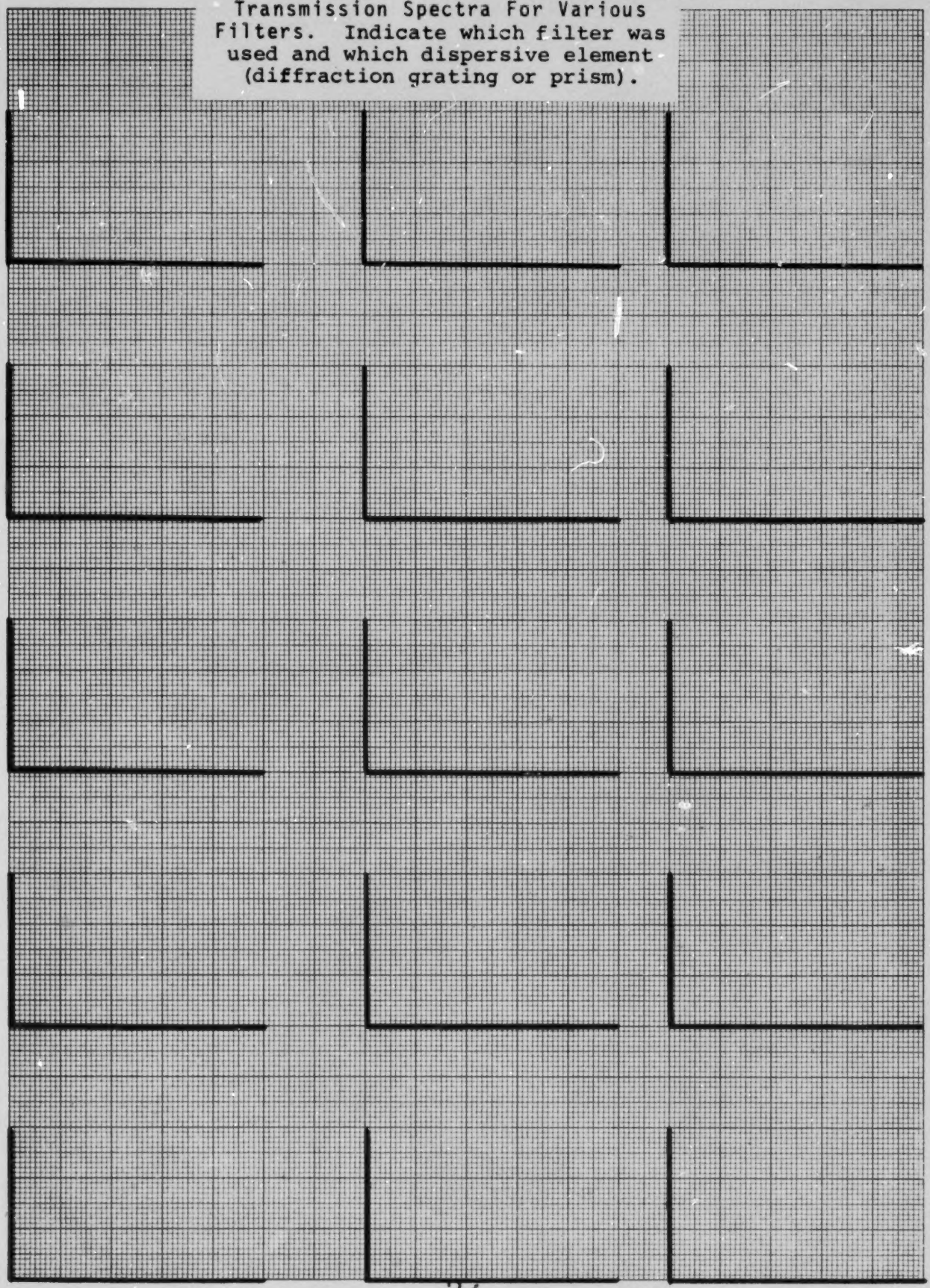
Also we need a more precise way of specifying colors. Red, orange, yellow, etc. are only general terms. Exactly where in a spectrum one color ends and the next begins can only be estimated, and the estimate will vary from person to person. In the next section we will introduce the term *wavelength* as a specification for color and show how it derives from our understanding of the wave nature of light. We will also extend the notion of wavelength to regions of the spectrum that our eye cannot "see".

- CALCULATIONS -

Transmission Spectra For Various Filters. Indicate which filter was used and which dispersive element (diffraction grating or prism).

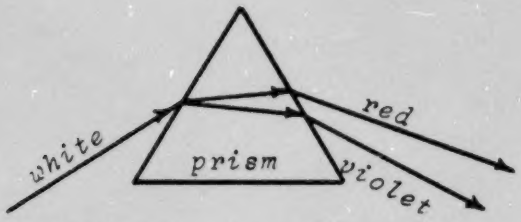


Transmission Spectra For Various Filters. Indicate which filter was used and which dispersive element (diffraction grating or prism).

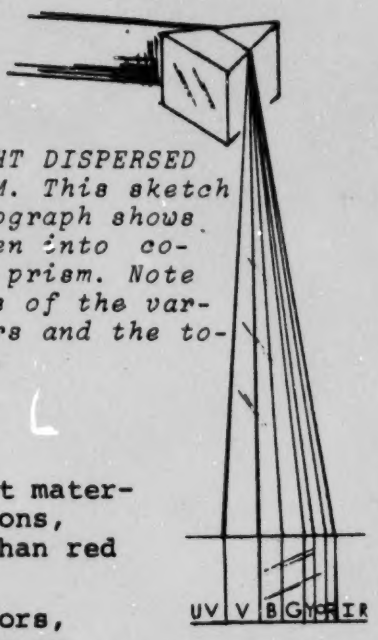


THE DISPERSION OF LIGHT

THE KEY TO A MONOCHROMATOR IS A DISPERSIVE ELEMENT — EITHER A PRISM....



AN EXAGGERATED DIAGRAM showing the different paths taken by red and violet light. Other colors fall between these two. The actual difference in paths is not nearly as great as shown.



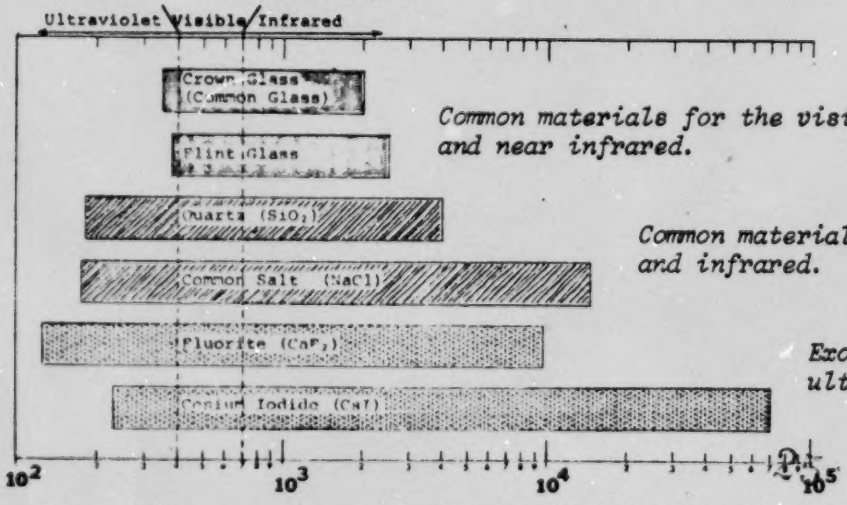
WHITE LIGHT DISPERSED BY A PRISM. This sketch of a photograph shows light boken into colors by a prism. Note the widths of the various colors and the total width.

PRISMS

A prism is simply a wedge of transparent material which bends light. For complicated reasons, violet light is more sharply bent by glass than red light.

A prism works best only for certain colors, leaving the rest still bunched together. For example in the illustration above violet is seen to be quite widely spread out while orange and red are still quite compressed. To surmount this problem, prisms are made of different materials to work in different parts of the spectrum. For example, prisms made of common table salt are used in the infrared part of the spectrum.

The illustration below shows the useful range of various materials. The wavelength numbers will have more meaning as you go farther in the module.



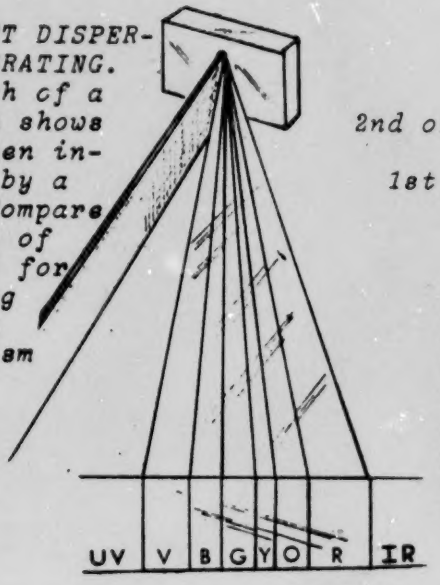
Common materials for the visible and near infrared.

Common materials for the ultraviolet and infrared.

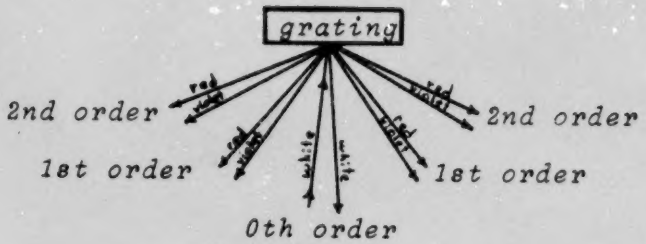
Exotic materials for the far ultraviolet and far infrared.

—SOMETHING WHICH BREAKS WHITE LIGHT INTO COLORS

....OR A DIFFRACTION GRATING



WHITE LIGHT DISPERSED BY A GRATING. This sketch of a photograph shows light broken into colors by a grating. Compare the widths of the colors for the grating with those of the prism opposite.



GRATING REFLECTIONS come off at the unexpected angles. The white light coming in can be simply reflected -- the so-called 0th order. This is not dispersed. The other orders are on either side and are dispersed.

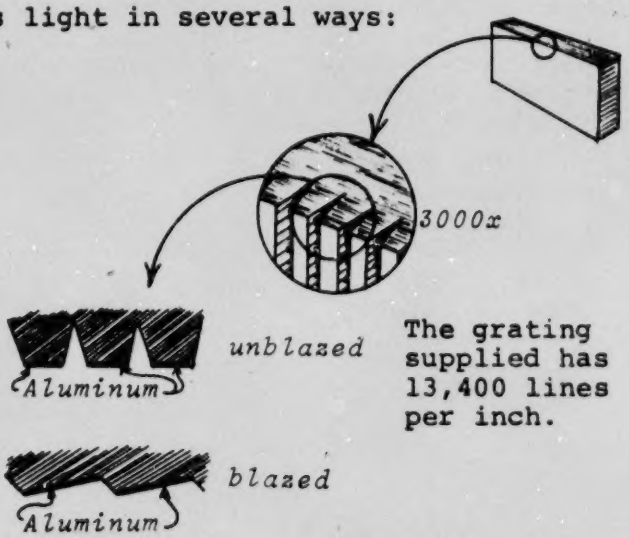
GRATINGS

A reflection grating is a front surface mirror with thousands of fine, parallel scratches on it.

A grating always reflects light in several ways:

- 0th order: straight reflection, like a mirror;
- 1st order: on both sides of the 0th order a spectrum appears; one side can be made brighter by *blazing*;
- higher orders give weak additional spectra that sometimes overlap the previous order spectra.

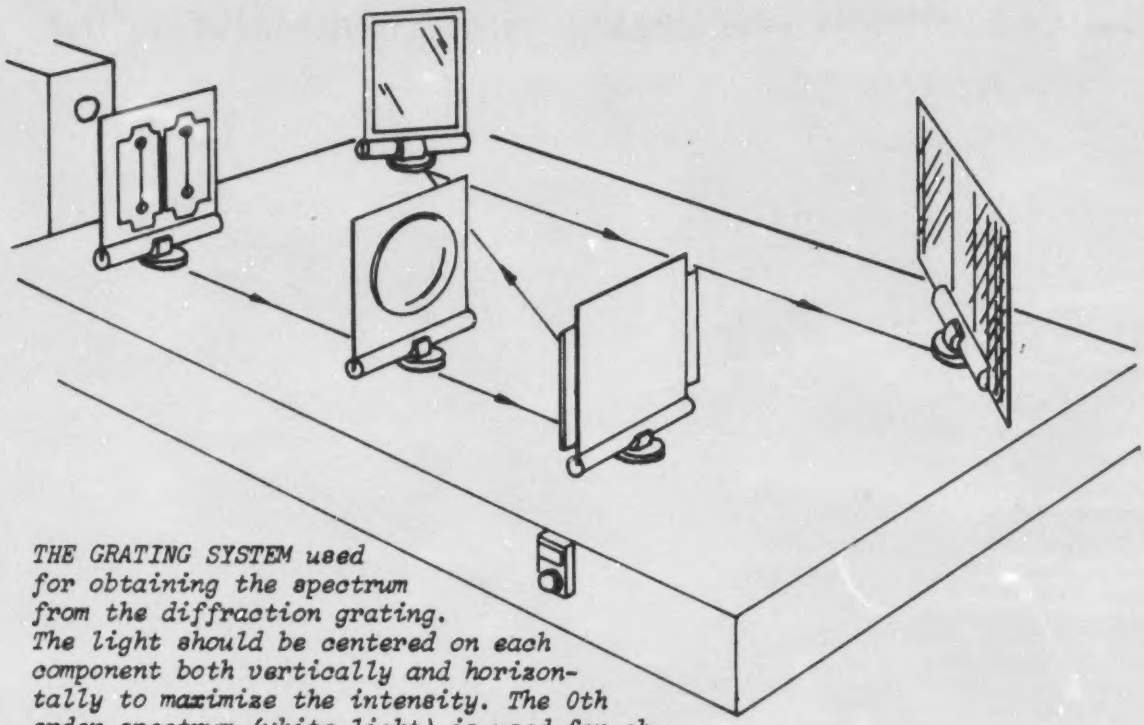
The diffraction grating separates the colors much more evenly then the prism as the illustration above shows. However the intensity of the light is less than the prism because the incoming light is divided into several spectra as well as a simple reflection.



The grating supplied has 13,400 lines per inch.

A MAGNIFIED VIEW of a grating, showing the difference between blazed and unblazed gratings.

AN EXPERIMENT COMPARING A PRISM AND A GRATING



THE GRATING SYSTEM used for obtaining the spectrum from the diffraction grating. The light should be centered on each component both vertically and horizontally to maximize the intensity. The 0th order spectrum (white light) is used for obtaining exact component positions, and either 1st order spectra (left or right) may be used for the measurements.

INTRODUCTION

The point of this investigation is to discover experimentally what a dispersive element does and in what ways this is done differently by a prism and a grating. The spirit of the lab is exploratory--observe what happens when you change things around. This process should raise questions which will be answered later in this module.

The set up we will use first is illustrated above. It is quite similiar to the previous experimental arrangement. The only change is that there is a longer light path from the dispersive element to the card where the spectrum is viewed. This is accomplished by reflecting the light once from a mirror. The result is that the spectrum is fainter but proportionally larger and easier to measure.

PROCEDURE

STEP 1: ALIGNING THE GRATING SYSTEM.

Obtain the paper template titled COMPARING A PRISM AND GRATING and tape it securely to the base and centered on the center hole (see the illustration on the next page).

Place the slit and lens in the indicated positions. Also place the grating at 1 , mirror at 2 and card at 3. Irregularities in manufacturing may require you to move your components somewhat around these positions to get the maximum amount of light squarely through each element.

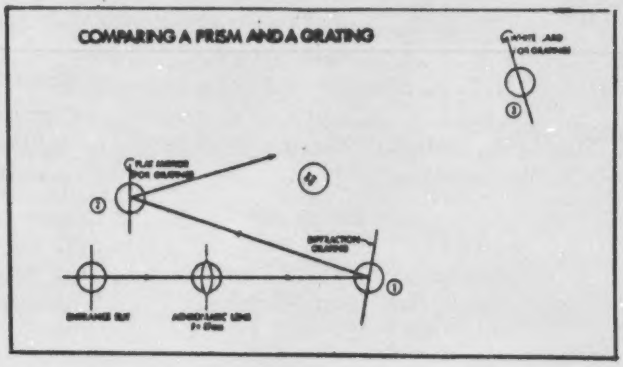
To focus the lens properly, turn the grating to get a white image of the slit (the 0th order) on the white card then move the lens back and forth to make the width of this image as narrow as possible. Be sure that the white light strikes each element at its center, both horizontally and vertically. This may require some tilting of the elements on their base.

When you think the system is properly aligned, check the system by following the beam until a white card as in part one or by putting some smoke from incense into the box.

STEP 2: LOOK AT THE SPECTRUM.

Turn the grating (without changing its position) to get a spectrum on the card.

* How many orders can you see on either side of the centered image?
* Are the same orders on either side identical?
* How do the brighter orders compare to the 1st order with regard to width and intensity?
* Do the orders overlap?



THE LAYOUT used in this experiment is very similiar to the previous layout shown on page 10. When the grating is used at 1 , the mirror goes at 2 and the spectrum appears on the card at 3 . When the prism is used, the mirror and card should be reversed. This arrangement keeps the same optical path length from dispersive element to card for both prism and grating so that they may be exactly compared.

Now, look carefully at the 1st order spectrum. These colors should be the pure spectral colors. In particular, note the narrow pure yellow and the beautiful emerald green.

The spectrum is as interesting for what colors are missing as much as for the colors present. There is no brown, black, white or any of the pastel colors like pink; all these are mixtures of spectral colors. Also it is an odd fact that some spectral colors can also be made by mixing other spectral colors, for instance green can be made by mixing spectrally pure blue and yellow, but there is also a pure spectral green. Other colors like brown and purple can *only* be made by mixing spectrally pure colors (red and blue for purple).

You can easily spot a spectrophotometer that is not working well by looking at its spectrum. You can often observe both missing colors (especially emerald green and yellow), and also non-spectral colors (especially pastel blue and white).

STEP 3: WHY SLITS & LENSES?

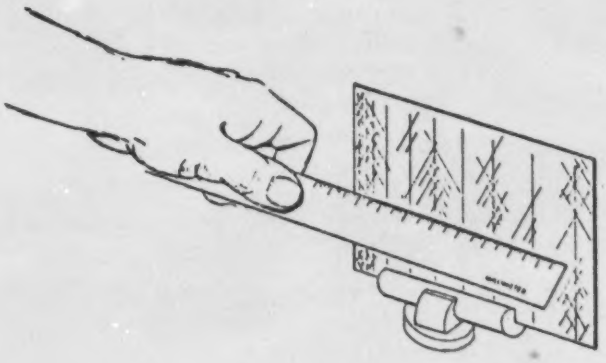
Explore the effect of removing both the slit and lens separately. Also try mis-alignment of all the elements, sideways and back and forth. Try this with smoke from incense in the box so that you can see the effects more clearly. You should be able to determine the reasons for having these elements where they are.

Return the elements to their proper positions and refocus the system. Use the 1st order spectrum that results in red being at the right side of the card. Get the brightest possible spectrum you can, centered on the white card. Adjust the white card so that it is at exact right angle to the incident light.

Be sure that no "stray" light is falling on the card. The other order spectra are coming off the diffraction grating and may have to be blocked out with shields (the backs of optical components not being used will work nicely).

STEP 4: MEASURING THE GRATING SPECTRUM.

Place a ruler so that its zero is at the red edge of the spectrum (as shown in the diagram). Record the location on the ruler of the center and of the boundaries between each of the following colors: red, orange, yellow, green, blue & violet. Also record the location of the violet end of the spectrum. Your distances can only be best estimates using your eye. You will be surprised, later in the module, at how well you have done.



WHERE A GOOD BRIGHT SPECTRUM is observed on the white card, place a millimeter scale so that zero is where the red first appears. Record the distance to the centers and the boundaries of each color and record it in a table like that shown on the next page. Leave an extra column next to the various colors.

Make a clear, neat table of color boundaries as shown on the next page. Use the designated page at the end of this section for your data table. These important data will be refered to later.

A Final Measurement: Now rotate the grating until the 0th order spectrum (white light) appears on the screen. Measure its width and record it. This is the *width of the image of the entrance slit.*

Width of entrance slit image.

_____ *mm*

Color		Distance (mm) Grating	Prism
Red edge		0	
center		12	
Orange edge		21	
center		29	
Yellow edge			

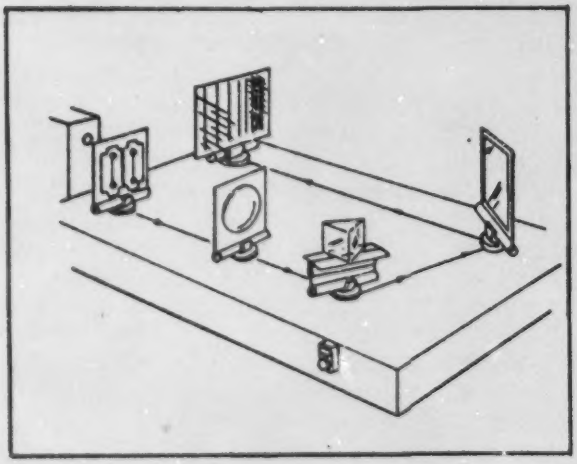
STEP 5. ALIGNING THE PRISM SPECTRUM.

Replace the grating with a prism, as shown in the illustration below. Do not move the lens or slit. Place the mirror at 3 and the card at 2 . Follow the same alignment procedures described earlier for the grating.

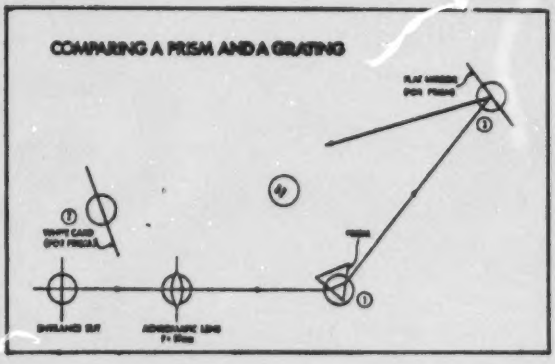
Rotate the prism (without changing its position). What happens to the spectrum? Adjust the rotation until the red part of the spectrum reaches its maximum left position. This position is called the *angle of minimum deviation* and gives the least mixing of colors.

Put smoke from incense in the box and observe the light paths. Note that at the angle of minimum deviation, the angle the light makes with the entering side of the prism is the same as the angle it makes with the exiting side.

Make sure that the white card is at exact right angles to the light striking it.



THE PRISM SYSTEM. Replace the grating with a prism and interchange the flat mirror and white card. The prism should be rotated to give the angle of minimum deviation. This occurs when the spectrum is at its maximum left deflection on the card.



THE LAYOUT of components as seen from above. The distance from the dispersive element to the card is identical to the previous arrangement so that the two spectra can be compared exactly. The next page suggests some comparisons that can be made.

STEP 6: MEASURING THE PRISM SPECTRUM.

Place a ruler so that its zero is at the red edge of the spectrum as you did in Step 4 for the grating. Measure the distance to the color centers and boundaries as you did before and record it in your table.

STEP 7: COMPARING THE PRISM AND GRATING.

Compare the spectra obtained for the prism and grating. You may want to set one system up on your spectrophotometer and the other on your neighbor's; or see if you can produce both at the same time on one set up. If you do the latter be sure that the total distance from dispersive element to white card is identical for each system.

Grating		Prism
	Brightness	
	Dispersion	
	Linearity	
	Purity	

Make a table like that shown to the right. Use the designated page at the end of this section for your table. Some of the properties of the two elements that you can compare are:

BRIGHTNESS: Which element produces the brighter spectrum, that is has the higher intensity of light in each color? Why is it brighter?

DISPERSION: Which element spreads out or disperses the white light into its component colors more? If an exit slit of a certain size were used to let only one color pass, which element would yield the narrower band of color?

To find out what actually happens, put an exit slit in place of the white card and put the white card behind the slit. Then scan the spectrum across the slit by rotating the flat mirror. Observe the beam of light that gets through the slit. How pure is each color for the prism?. . for the grating? What influence do you think the width of the slit makes on color purity?. . . . on intensity?

LINEARITY: Which element spreads the colors out more evenly?

PURITY: Which of the elements produces colors which may be a slight mixture? Why does this happen?

If any other differences are apparent note these in your table.

WHY ARE THE SPECTRA DIFFERENT?

We now have gone as far as we can without theory. We have a short catalogue of interesting observations about prisms and gratings. Still, some fundamental questions remain: What are the principles behind these observations? How are these observations related to other properties of light? How will different prisms and gratings differ in their dispersion?

Before we answer these questions, we must first learn a bit about light and its measurement. One crucial point is that light acts in many ways like a wave. As a wave it can be described by its wavelength. Visible light is simply one type of a more general class of radiation, called electromagnetic radiation. In the following pages we discuss the wave properties of light and see how it fits into the more general picture. Using the wave properties of light we will be better able to understand the operation of prisms and gratings.

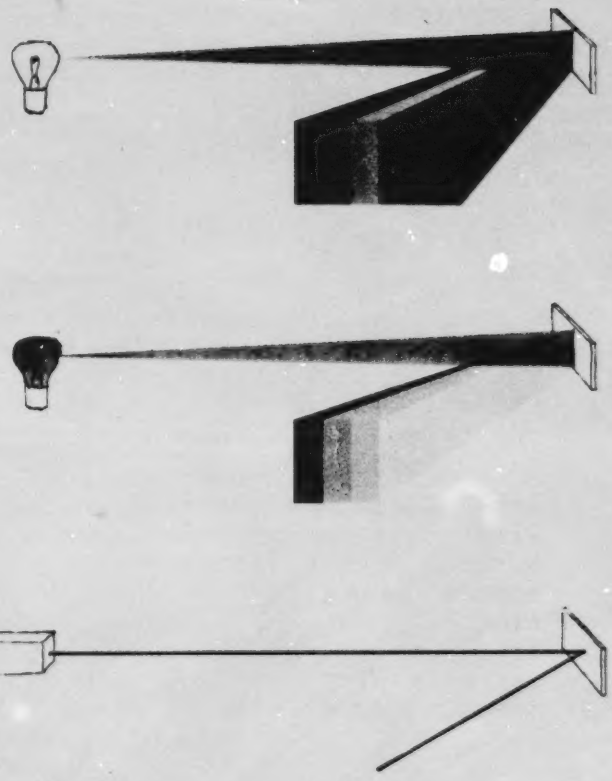
LIGHT AS WAVE MOTION

THE ELECTROMAGNETIC SPECTRUM

THE COLORS IN LIGHT

Light consists of various colors. The light we usually see, from the sun or light bulbs, for example, is a mixture of many colors. A prism or a diffraction grating is able to spread this mixture into its component colors forming what is called a *spectrum*. When water droplets do this, you see the spectrum as a rainbow.

The drawings at right show a diffraction grating forming a spectrum with white light from a light bulb. This is compared to the effect the same grating has on other colored lights. The conclusions are clear: all the light of a single pure color is bent the same amount; similiar colors are bent nearly the same amount so they end up near each other; colors which are quite different are spread far apart. You observed this in the experiments you have done.



THE COLORS OF LIGHT. These drawings show the composition of different types of light. In each case the same grating splits the light into its pure components. In a) white light is used; in b) light from a red bulb; and in c) a pure red light from a laser.

THE ELECTROMAGNETIC SPECTRUM

The light we see with our eyes -- visible light -- is only a part of the spectrum. There is a vast range of radiation called *electromagnetic radiation* which appears as radio waves, microwaves, infrared, ultraviolet, x-rays and gamma rays (see the chart opposite). These types of radiation all obey the same laws and travel through a vacuum at about 300,000,000 meters per second, or 186,000 miles per second.

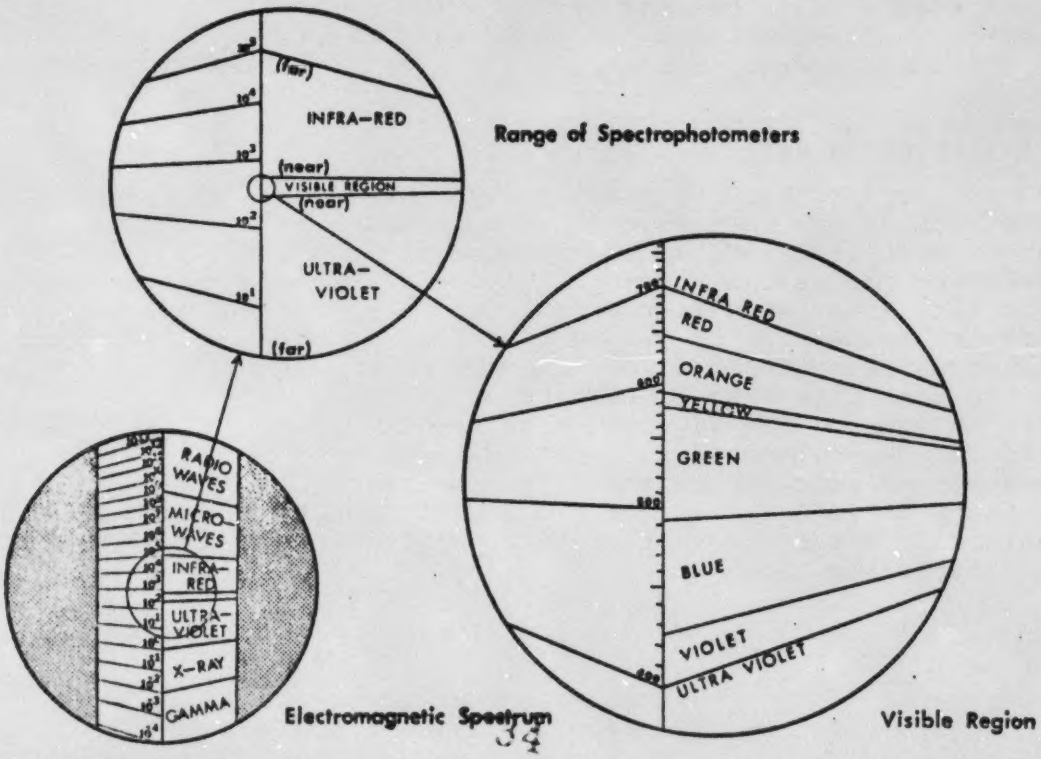
THE ACCIDENT OF VISIBLE LIGHT

Visible light happens to occupy only a tiny slice of this huge range. It is visible only because certain molecules in the retina of your eye are sensitive to light in this range. When this wavelength light strikes a sensitive molecule, it can relay the information through nerves to your brain. This way you become aware of the light and call it visible. If we had different sensitive molecules in our retina, we might call light of some other wavelength visible light.

RANGE OF SPECTROPHOTOMETERS

Spectrophotometers are used for measurements in three regions of the electromagnetic spectrum: the infrared, the visible and the ultraviolet. Each region presents particular design problems, so that rarely can a single instrument cover more than one region without modifications. The student spectrophotometer is basically for the visible region, although near infrared can be measured with suitable detectors.

No single prism or grating can disperse electromagnetic radiation of all wavelengths. The only way to alter the range of a prism is to make it out of some other material. Prisms can be made (see page 19) with ranges between 150 nm and 70,000 nm, although some of these are quite expensive and difficult to preserve. One substance sometimes used for prisms is common table salt in the form a single large crystal. Of course, such prisms must be kept away from water and even humid air! Gratings are much easier to alter in order to change their useful range. By simply changing the distance between the scratches that make up the grating one can obtain almost any range for a grating.



THE ELECTROMAGNETIC SPECTRUM includes waves longer than the diameter of the earth and shorter than the diameter of an atomic nucleus. A small slice of this spectrum is covered by spectrophotometers. In the center of this range is visible light. The wavelength numbers given to each region will be discussed later in this section.

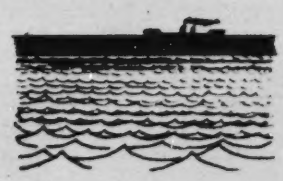
WHAT IS A WAVE?

FEATURES OF WAVES

Ocean waves, ripples on a pond, a wave on a rope, sound and light have one thing in common--they are all waves. All waves are started at a source that provides the energy to create waves. The wind can make ocean waves, a rock dropped into a pond is a source of ripples, the forced vibration of your vocal cords is a source of sound and the forced vibration of electrons is a source of light.

This energy moves as waves which are oscillations of some quantity. In ocean waves and ripples it is the height of the water which oscillates up and down; for waves on a rope, the height of the rope oscillates; for sound waves, the air pressure oscillates; for light, the electric and magnetic fields oscillate.

It is very hard to imagine oscillating electric and magnetic fields. However, if you were a tiny electron, you would know all about it. Whenever a light wave passed near you, it would make you jump up and down at a fantastic rate. The oscillating electric fields can exert a force on electrons and other electrically charged matter which is just as real as the force an ocean wave exerts on the shore when it breaks.



Ocean waves.

Waves on a pond.

Wave on a rope.

Sound waves.

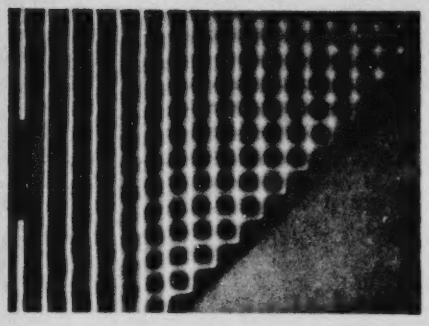
EXAMPLES OF WAVES. In every case something oscillates. Since it takes energy to make the oscillations, we say the waves carry energy.

WHY IS LIGHT A WAVE?

It is very hard to imagine light as a wave because the wavelengths are so small (about 2/100,000 inches) and because the waves are impossible to see anyway. To show that light acts like a wave, we compare the properties of simple waves to the properties of light. The illustrations on the next page show properties of ripples in water. The waves move perpendicular to the white crests, in the directions of the arrows. On the right the same property is illustrated for light using spectrophotometer parts and smoke. *It is because of these similarities that we can say that light acts like waves.*

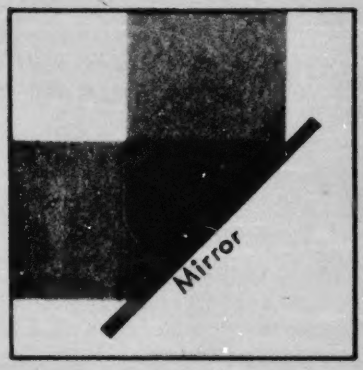
COMPARING THE PROPERTIES OF . . .

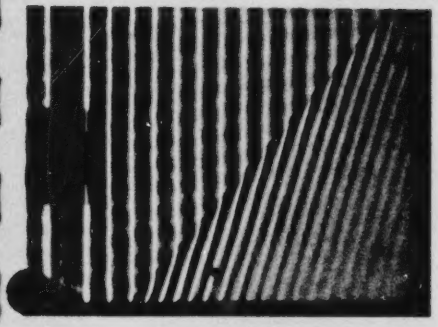
WATER WAVES and LIGHT WAVES



REFLECTION

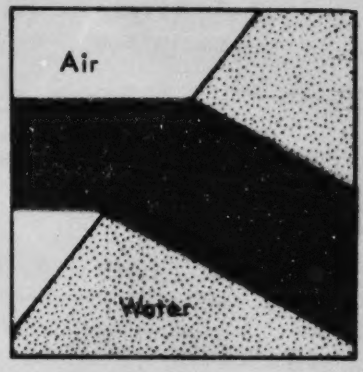
. . is the bouncing of waves off barriers. At the left, a block is in the water which the waves cannot penetrate. As a result, they bounce off in another direction. The same effect is illustrated at the right where the barrier is a silvered mirror. Can you see the rule for the angles involved in reflection?

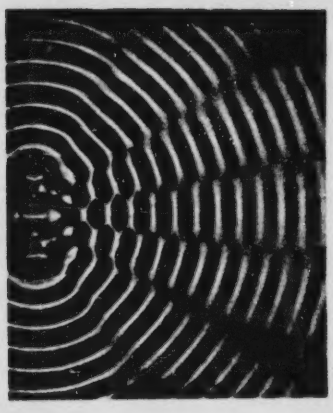




REFRACTION

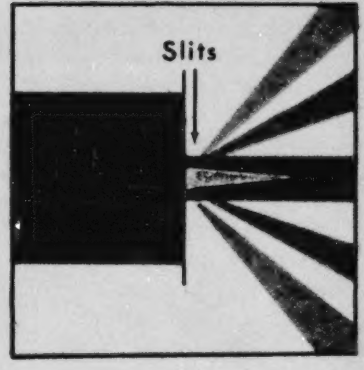
. . is the bending of waves when they change speed. In both illustrations there are two regions where the wave speeds are different. At the left the ripples travel from deep water to shallow water where the speed is reduced. At the right, light enters water where its speed is 3/4 of its speed in air.

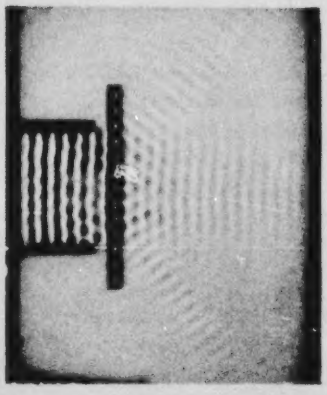




INTERFERENCE

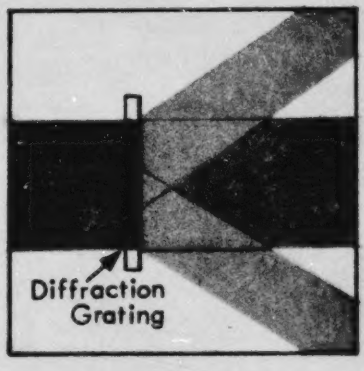
. . is the combining of waves in a given region. At the left, water waves radiate from two arms bobbing at the same frequency. The result is; regions of no water motion (destructive interference) separated by regions in which the waves are twice as high (constructive interference). Similarly two light sources of the same wavelength give rise to an alternating light and dark pattern.





DIFFRACTION

. . is the effect on waves produced by regularly placed obstructions. At the left, the obstructions are pegs in water. These cause the incoming waves to bounce off in unexpected directions. At the right, the pegs are replaced by thousands of regular scratches on the plastic of a transmission grating. Similar unexpected beams result.



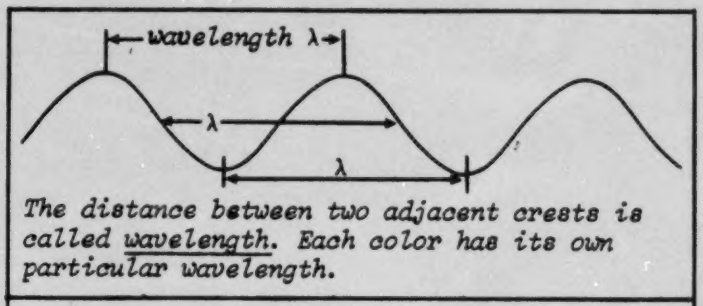
MEASURING LIGHT WAVES

HOW DO WE DESCRIBE A WAVE?

Three important quantities come up whenever you talk about a single pure wave -- its *wavelength*, *speed* and *frequency*. These are defined below:

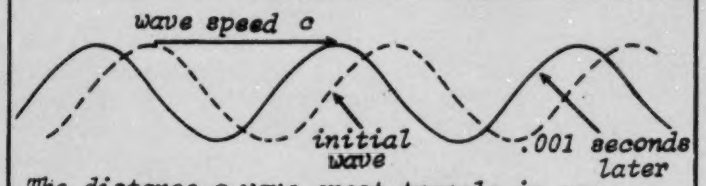
Waves of Violet Light (402 nm) Scale: 1 cm = 100 nm

Wavelength. If you take a photograph of a pure wave, it will show regular repeating cycles. The distance between identical points of two neighboring cycles is the *wavelength*. This is usually given the Greek letter λ (lambda) as in the illustration opposite.



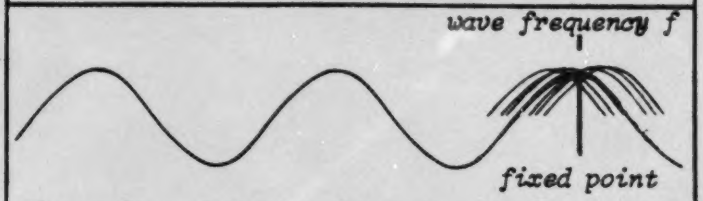
The distance between two adjacent crests is called wavelength. Each color has its own particular wavelength.

Speed. If you take a second photograph an instant after the first, you will see each cycle moved over a bit. The distance moved divided by the time required is the wave *speed*. The symbol c is often used for wave speed. For light in a vacuum $c = 3 \times 10^8$m/sec.



The distance a wave crest travels in one second is its speed. Light travels more slowly through matter and the speed of different wavelengths is different.

Frequency. You stand still as a wave moves past you and count the number of complete cycles passing. This number per second is the *frequency*, and is often given by the symbol f. Frequency is measured in cycles per second. This unit used to be abbreviated as cps, cycles, or sec^{-1}. Now the units used are *Hertz* (Hz) which simply means cycles per second.



The number of crests that pass a point in one second is the frequency. Frequency like wavelength is different for different colors.

LIGHT AS A WAVE

Since light behaves like waves, it is natural to measure its wavelength. The wavelengths of light are extremely small, about 2/100,000 of an inch. Each pure color corresponds to a wave of a different wavelength. Colors that are close together in a rainbow have wavelengths that are near each other. Thus, spectral colors can be classified and specified precisely by their wavelengths.

The speed of light waves is incredibly high, 3×10^8 meters per second, or 186,000 miles per second. That is 7.5 times around the earth in one second. No object, however small, can ever

go quite that fast; likewise, no signal or pulse can ever go faster. This speed is the speed of light in a vacuum. It is slightly less in air, and much less, for most wavelengths, in glass and most other transparent materials. This variation of speed with wavelength accounts for the dispersion by a prism, as we shall see.

Frequency can also be used to specify light colors. But only frequency *or* wavelength need be used, since one determines the other. Wavelength is much easier to measure, so it is more often used. The frequency of light is around five hundred million million cycles per second (5×10^{14} Hz). At present this is impossible to measure directly. In an importance sense, frequency is a more fundamental measure of light since, unlike wavelength, it does not depend on the speed.

A BASIC WAVE RELATIONSHIP

Wavelength, frequency and velocity are not independent of one another. There is a basic wave relationship among them so that if two are known, the third is fixed. We shall now get this relationship.

To simplify matters we need a new term, the *period* T. A period is the time in seconds for a complete cycle to pass. Period and frequency are very simply related. If the period is 1/10 sec., it means that a complete cycle takes 1/10 sec. Then there are 10 cycles per second and this is the frequency. In general if the frequency is x cycles per second the period is 1/x sec.. T and f are reciprocals. Put mathematically,

$$T = \frac{1}{f} .$$

There is a simple relation between period, T, wavelength, λ, and speed, c. Remember that for any uniform motion,

$$\text{the SPEED} = \frac{\text{the DISTANCE covered}}{\text{the TIME required}} .$$

A wave covers the distance of one complete cycle -- the wavelength, λ -- in the time for this cycle -- the period T. Doing this, it is going at the speed of a wave, c. Substituting in the basic speed formula gives

$$c = \frac{\lambda}{T} .$$

Multiplying both sides by T, we can solve for λ.

$$\lambda = cT.$$

Now remove the period T since it was simply introduced as a crutch. Since they are equal, substitute 1/f for T and get

$$\boxed{\lambda = \frac{c}{f}} \quad \textit{wave relationship}$$

This says just what we want, since it shows that larger frequencies correspond to small wavelengths.

The rate formula

$$\textit{speed} = \frac{\textit{distance}}{\textit{time}}$$

can be used for waves using

speed = c

distance = λ

time = T.

So

$$c = \frac{\lambda}{T} \text{ or } \lambda = cT.$$

T and f are inverses:

$$T = \frac{1}{f} ,$$

so

$$\lambda = \frac{c}{f} ,$$

or

$$c = f\lambda.$$

CHOOSING A SCALE FOR LIGHT

In order to use a spectrophotometer, we must be able to assign numbers to different parts of the spectrum. The rough estimates we have been using such as "blue-green" are not exact enough.

What we need is a scale for light that serves as inches on a ruler does for ordinary lengths. Unfortunately, there are over a dozen such scales in common use. For our work here, we will use the international standard unit. *We will describe electromagnetic radiation by its wavelength as measured in nanometers.* A nanometer (nm) is a tiny measure of distance equal to 10^{-9} meters or 10^{-7} centimeters. The chart on the next page gives the wavelengths in nanometers for various types of radiation.

1 cm (actual size)

1 mm (magnified 10 times)

100μ (magnified 100 times)

10 μ (magnified 1,000 times)

1 μ (magnified 10,000 times)

100nm (magnified 100,000 times)

10 nm (magnified 1,000,000 times

1 nm (magnified 10,000,000 times)

THE ANGSTROM AND OTHER UNITS

The international standard of length is the meter. Since wavelength is a length it should be measured in meters. Since *nano* is the prefix signifying 10^{-9}, the nanometer is the proper unit. However, many other units are used. The most common competitive unit is the *Angstrom* which is one tenth of a nanometer, or 10^{-10} meters. You will also run across the unit *millimicron* (mμ) which is identical to a nanometer.

m	= meter			$= 10^{2}$ cm	
cm	= centimeter	$= 10^{-2}$	meter		(centi = 10^{-2})
mm	= millimeter	$= 10^{-3}$	meter	$= 10^{-1}$ cm	(milli = 10^{-3})
μ	= micron (short for micrometer)	$= 10^{-6}$	meter	$= 10^{-4}$ cm	(micro = 10^{-6})
nm	= nanometer	$= 10^{-9}$	meter	$= 10^{-7}$ cm	(nano = 10^{-9})
mμ	= millimicron	$= 10^{-9}$	meter	$= 10^{-7}$	
Å	= Angstrom	$= 10^{-10}$	meter	$= 10^{-8}$ cm	

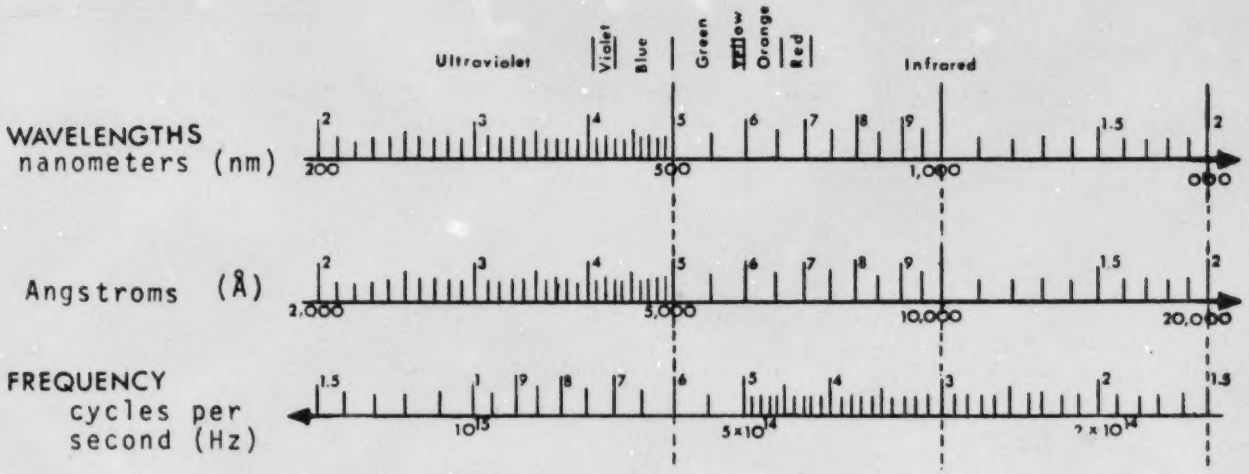
WAVELENGTH CONVERSIONS

To convert wavelengths in nanometers to wavelengths in other units of length, use the rules in the box below. Since all other wavelength scales are in decimal units, the conversions are relatively simple.

To convert a wavelength *from* nanometers			To convert a wavelength *to* nanometers		
to		multiply by	*from*		multiply by
meters	m	10^{-9}	meters	m	10^{9}
centimeters	cm	10^{-7}	centimeters	cm	10^{7}
microns	μ	10^{-3}	microns	μ	10^{3}
millimicrons	mμ	1	millimicrons	mμ	1
Angstroms	$\overset{\circ}{A}$	10	Angstroms	$\overset{\circ}{A}$	.1

UNIT CONVERSIONS

Sometimes colors are expressed as frequencies. The chart below allows you to easily convert these to Å or nm. The text on page 32 explains how to calculate these conversions more accurately than the chart can.



THE CHART. With the use of this chart, conversions between common spectrophotometer units can be made quickly without calculations. The only drawback is that it has less than two-digit accuracy.

To use the chart, simply locate the known quantity on one scale and then draw an imaginary vertical line at that location to the scale of the desired equivalent unit. A clear plastic ruler will be a great help in this. For example, locate $4.5x10^{14}$ cycles per second (Hz). Tracing a vertical line upward shows that this is equivalent to 6,600 Angstroms.

THE WAVELENGTHS OF LIGHT

LIGHT AND WAVELENGTHS

Light that we can see has wavelengths between 400 nm and 700 nm. The chart at the right shows the approximate wavelength of each of the colors we have seen.

Color	Wavelength (nm)
Ultra-violet/violet edge	*385*
Violet center	*402*
Blue/violet edge	*424*
Blue center	*458*
Green/blue edge	*491*
Green center	*533*
Yellow/green edge	*575*
Yellow center	*580*
Orange/yellow edge	*585*
Orange center	*616*
Red/orange edge	*647*
Red center	*690*
Red/infra-red edge	*730*

It is difficult to say exactly what wavelength each color is, because the colors in the spectrum merge slowly from one to another. The chart at right, which shows the accepted ranges of the primary colors, should not be taken too seriously. First, as you have seen, there is no sharp boundary between colors. Secondly, within each primary color range are a number of shades.

While noting these exceptions, it is interesting how uneven the color widths are. In particular, note how narrow yellow is compared to green and red. Does this correspond to your laboratory observations?

Wavelengths can also be assigned to radiation that we cannot see. Radiation with wavelengths *larger* than the longest red is called *infra-red*. Radiation with wavelengths *smaller* than the shortest violet is called *ultra-violet*.

WAVE NUMBER

An altogether different unit is often used for light called the *wave number*, k. The wave number is defined as the reciprocal of the wavelength,

$$k = \frac{1}{\lambda} .$$

Most often this is given the units cm^{-1} or reciprocal centimeters. For instance, a 10^{-4} cm wavelength would be assigned a wave number of 10^{4} reciprocal centimeters.

Wave number is defined as

$$k = \frac{1}{\lambda} .$$

ANALYZING YOUR CURVES...

...USING WAVELENGTHS

INTRODUCTION

The data from your experiment can now be analyzed in terms of wavelengths. The measurements consist of the locations of colors produced from both a grating and a prism. The central question is; What is the *relation between the location of the colors and their wavelengths,* for both the prism and grating?

GRAPHING YOUR DATA

The simplest way to analyze your data is to graph it. We will graph the observed locations of each color on one axis and the wavelength of the color on the other. Hopefully, the graph of these points will reveal some simple relationship between locations and colors.

An example of how to treat your data is provided below. The data shown is similiar to yours, but applies to other dispersive elements. To plot your data in this form follow the simple steps below. Graph paper is provided at the end of this section.

1. *Convert the color boundaries* to wavelengths in nanometers using the wavelength chart on the opposite page.
2. *Graph these wavelengths* against the distance each color appeared as measured from the red -- infra-red boundary. Do this on the same graph for both the prism and the grating. Plot distance on the vertical axis and wavelengths on the horizontal.
3. *Draw the curves* for both the prism and the grating. A straight edge or draftsman's french curve may help you to obtain smooth curves. Remember that for the best curve, the number of points that are off the line above (and their distance) equals the number that are off below.
4. *Write at the top of the graph* the colors corresponding to the wavelengths along the horizontal axis. This is useful to remind you where the original data came from.
5. *Label the axes* and place a title on the graph to remind both yourself and others what the graph is supposed to show.
6. *Draw two horizontal parallel lines* separated by the measured width of the 0th order. This will give an indication of how well your spectrophotometer could separate two colors.

TYPICAL DATA for two dispersive elements different from those you used. This suggest how you may graph the data you have taken from your experiment.

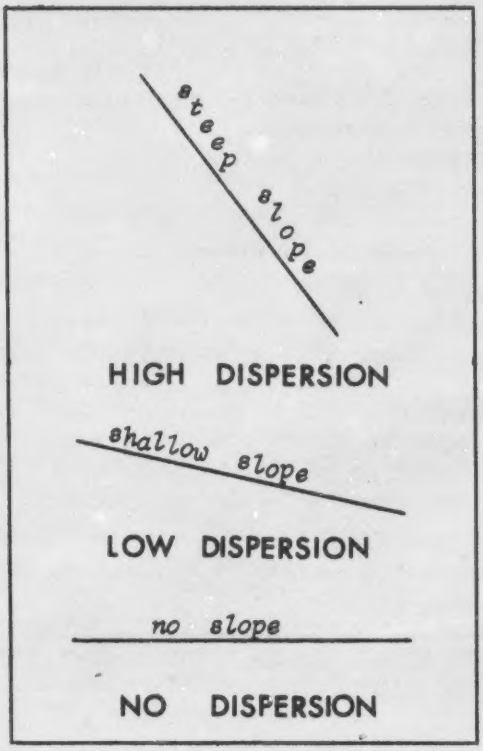
DISPERSION

At this point, it is useful to define the word *dispersion* to help you interpret your graph. Dispersion refers to the amount that the colors are spread out. It has an exact mathematical definition which we will tackle later when we have better data. For now, it is sufficient to say that *the more the colors are spread out, the greater the dispersion.* Look at *your* graphs with this idea in mind. How can you judge the dispersion from the graphs? Which element has greater dispersion?

Several facts about the dispersion in your graphs are:

1. *The dispersion is proportional to the slope of your graph.* A steep slope implies that slightly different wavelength colors are found at quite different positions; this is what we mean by "spread out". A shallow slope means that even widely separated colors are found at nearly the same position; not spread out. A horizontal line with zero slope results from adjacent colors landing at the same spot and is a case of no dispersion or spreading at all.

2. *The dispersion of some dispersive elements depends on wavelength.* If one of your graphs is curved, then its slope is changing. As a consequence, the dispersion is changing. In the graph on page 36 the slope and dispersion of one is constant, but is changing for the other.



STUDY QUESTIONS

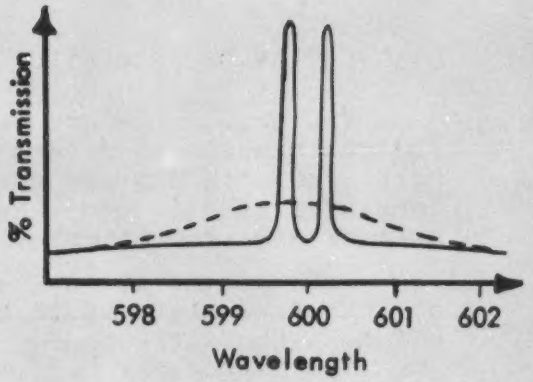
Armed with these ideas, you should be better able to interpret your data. Try answering questions 5 through 9 on page 46 at this time.

RESOLUTION

INTRODUCTION

Suppose your didymium filter had some very sharp details around 600 nm that looked like the graph at the right.

These details would be completely lost in your student spectrophotometer. They are too fine to be "seen" or *resolved* by this instrument. A precision instrument which could resolve details as small as .1 nm would be needed; your instrument cannot see details finer than about 10 nm.

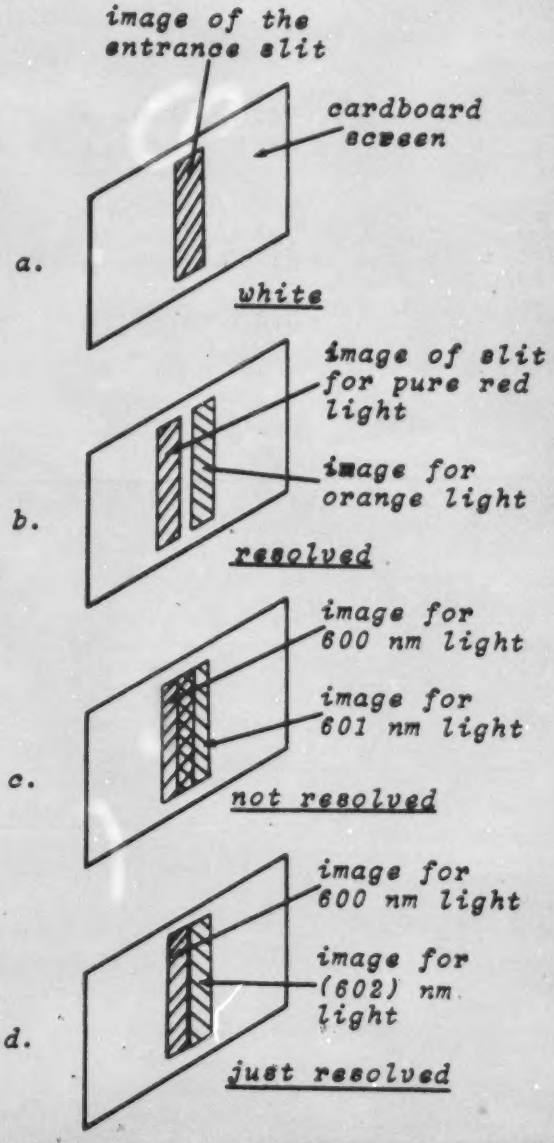


DETAIL OF A SPECTRUM that you would miss with the student spectrophotometer. You would observe the dotted line with a resolution of about 1 nm.

THE BASIS OF RESOLUTION

The limiting factor in resolution is the width of the image of the entrance slit at the spectrum. You were asked to measure this width in the second experiment. We will now use that measurement to determine resolution.

An absolutely pure red light (from a laser perhaps) would make a rectangle on the card the same width as the white light rectangle. Both rectangles are images of the entrance slit (see a and b at the right). Two pure colors cannot be clearly distinguished if they overlap as in c. The colors can be just distinguished, or resolved, when their images just touch, as in d. The distance between the centers of these two rectangles is the same as the width of either rectangle. You can use your calibration chart to convert this distance into the difference in nanometers between the just-resolved lights. This difference can be defined as the *resolution*.



CALCULATION OF RESOLUTION

You should now use your measured *entrance slit image width* and calibration to determine the resolution of your spectrophotometer for both a prism and a grating for at *least* three wavelengths. To help you, the calculations are described here for another spectrophotometer which as a 10 mm wide image of the slit.

Look at the point A at 400 nm on the graph on page 36. Light of that wavelength would be spread 5 mm above and 5 mm below that point. This corresponds to 384 nm and 416 nm. The resolution is then the difference between these, *32 nm.* A similar analysis for the prism shows its resolution at 400 nm to be only 17 nm.

1. *Determine the resolution* of your prism and grating at the following wavelengths:

   400 nm

   550 nm

   700 nm

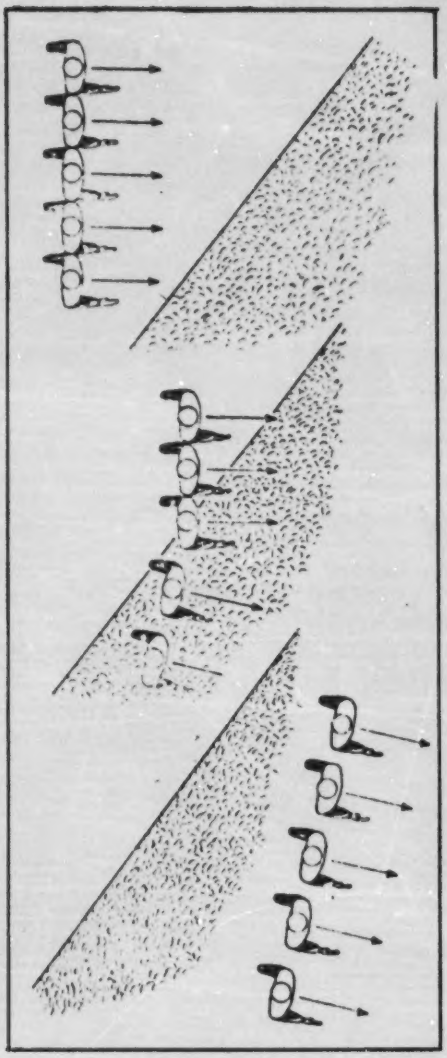
2. *Record your results* in the space provided on the page at the end of this section.

From your data which dispersive element has higher resolution in the red? in the blue?

At which wavelength are they equal?

- CALCULATIONS -

THE PHYSICS OF PRISMS AND GRATINGS



AN ANALOGY. If the band goes slower in the grass, it must bend. Substitute light waves for the rows of players, and glass for grass. Then you see why light bends if it must go slower.

INTRODUCTION

Physicists are always asking how things work. Prisms and gratings are no exception. In fact, they illustrate some extremely important ideas. Therefore, we will take a short break from the spectrophotometer to briefly explore these ideas.

PRISMS:

The first question to ask about prisms is why light bends or *refracts* when it enters glass. The answer has to do with the fact that the speed of light is slower in the glass. You can see this same effect in the following imaginary experiment.

A MARCHING BAND REFRACTS

Imagine a marching band which has been given two orders:

1. March at half speed on the grass.
2. Always keep your shoulder in line with the man on each side.

Now, look at what happens when the band approaches the edge of the grass at an angle. The sketches at left are an aerial view of the situation. Look carefully at the first row. As the second sketch shows, the first two players on the grass lag behind the row because they are marching slowly. To obey order #2, they must turn leftward and march at a different angle. This illustration is only an analogy. However, it does show what happens to light; it is bent when it enters a region in which it goes more slowly. This effect is called *refraction*.

The important point is that the amount of bending, or *refraction* depends on the speed in the glass (or grass). The *index of refraction* is a number you will often encounter. It gives the relative speed of light in a material. It is simply the ratio of the speed of light in a vacuum, c, to the speed of light in the material, v. If n is the index of refraction, then,

$$n = \frac{c}{v} ;$$

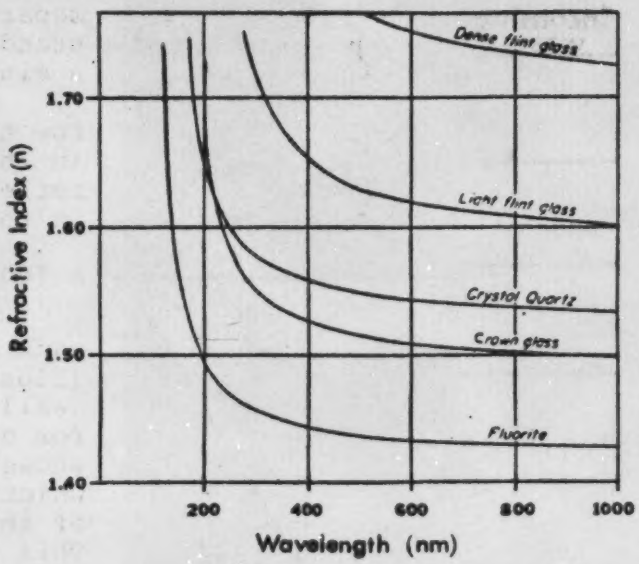
Values of n for common materials are given in the graph on the opposite page.

SPEED AND WAVELENGTH

The index of refraction does not explain the way a prism separates colors. One more idea is needed. The missing key is the following:

For a given material, the speed of light is different for different wavelengths. This effect which you observed in your experiment is called *dispersion*. Since light bending depends on the speed of light, different wavelengths are bent different amounts. Therefore, it is dispersion which causes a prism to form a spectrum.

The graph opposite shows how the speed of light changes with wavelength for various prism materials. Wavelengths for which the speed is changing most rapidly are spread apart most. You can see why the blue end of your prism spectrum is more spread out than the red. Compare the shape of the curve for light flint glass with your dispersion curve for the prism.



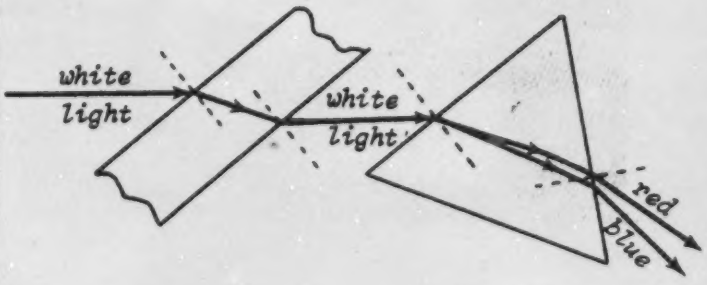
LIGHT SPEED VARIATIONS cause the index of refraction to be different for different wavelengths of light. This graph shows the index of refraction for various materials used in prisms and lenses.

DISPERSION IN PRISMS

Dispersion is *not* seen in window glass because the light bends one way on entering the glass and the other way on leaving it. This cancels the dispersion. A prism is constructed as it is so that the light must bend the *same* way entering and leaving the glass. According to our previous discussion, light travels more slowly in glass than in air. Therefore it bends toward the perpendicular when it enters glass but away from the perpendicular when it enters air. Notice how the design of the prism results in a double bending of the light. In fact the 60°-60°-60° prism you used is the shape that gives the greatest dispersion of the spectrum for the least loss of light.

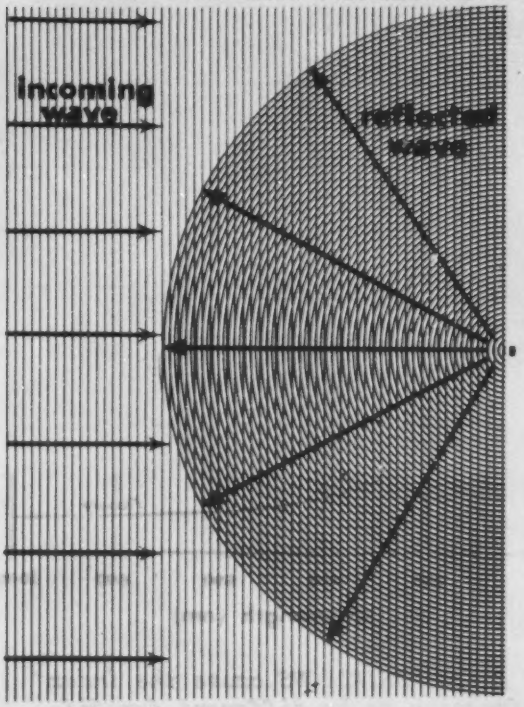
Material	Refractive Index
Air	1.0028
Ice	1.31
Water	1.33
Ethyl Alcholol	1.36
Plexiglass	1.49
Common Salt	1.54

The index of refraction for some common materials for yellow light.

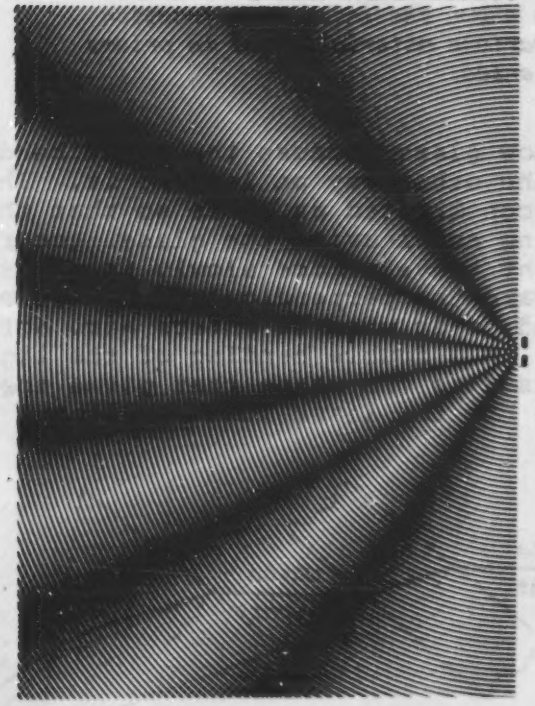


Flat Window Glass *60°-60°-60° Prism*

ONE MIRROR REFLECTION



TWO MIRROR REFLECTION



GRATINGS

A reflection grating consists of many parallel strips of mirror separated by scratches. To understand how it works, let's look at a single mirror strip first.

Each mirror strip is so narrow that it does not reflect light in the usual manner. Instead, it reflects rings of waves, as shown in the view-from-above at left.

A TWO STRIP GRATING

Two neighboring mirror strips each send out similar rings. The illustration below shows this (while omitting the incoming wave for clarity). The illustration shows vivid light and dark rays which are caused by the crossing of the two sets of concentric rings. This illustration is identical to the water wave picture of *interference* on page . Take a moment to look at that photograph.

Now let's look carefully at the drawing. The black rings in the drawing mark the crests or high points of the waves, and the white areas mark the valleys or low points. At the lighter regions of the drawing the black rings from the two mirrors lie on top of each other. Here the crest of a wave from one mirror adds to a crest from the other. This is called *constructive interference* and results in a stronger wave where the drawing is lighter. On the other hand, the darker regions in the drawing occur when crest is added to valley. There the waves cancel *(destructive interference)* and there is no light.

To summarize: There is light at the light region in the drawing but no light in the dark regions.

THE ORDERS OF THE SPECTRUM

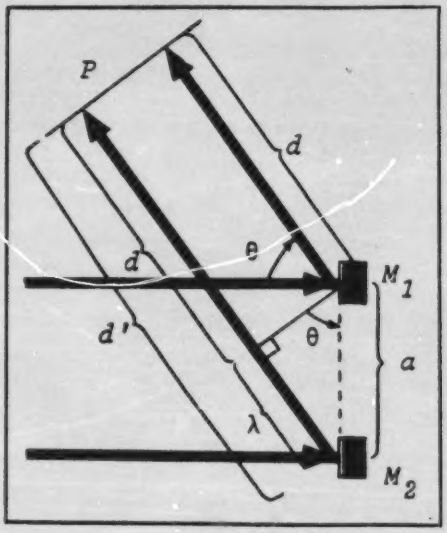
The light areas make several beams of light. One beam comes back perpendicular to the mirrors. This is called *zeroth order* beam. On either side are symmetric beams of *first order*, and so on. Look closely at the first order. If you count rings, you will see that the fifth ring from the nearer mirror overlaps the sixth from the farther mirror. This is true for all the rings in the first order: you are always one ring, or wavelength, farther from one mirror than the other. This is what causes the first order -- *a one-wavelength difference between the distances to the two mirrors.*

ORDER ANGLE AND WAVELENGTH

This fact makes it possible to relate the wavelength to the angle the first order makes with the zeroth order. The point P on the first order is a distance d from mirror number one, M_1, and d' from M_2. The mirrors are a distance a apart. All we know about d and d' is that their difference is λ, one wavelength. This allows us to construct the right triangle in the illustration. For this triangle

$$\sin\theta = \frac{\lambda}{a} .$$

The important point is that the equation requires that different wavelengths go through different angles.

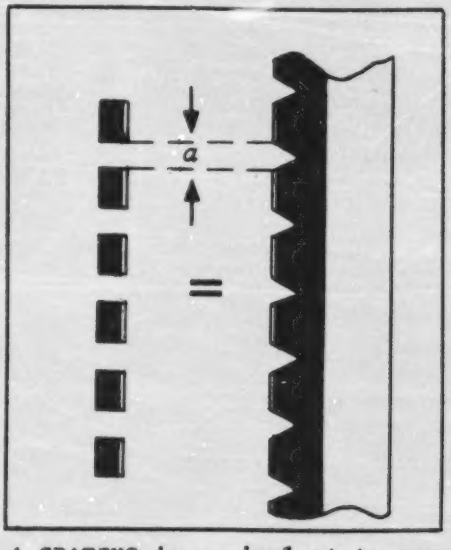


THE GEOMETRY OF REFRACTION. The lower beam must travel one wavelength farther to reach P than the upper one.

REAL GRATINGS

Diffraction gratings can be thought of as being made of many strip mirrors placed next to each other. The center of each mirror is exactly a distance a from its neighbors. Every pair of strips produces a beam at an angle θ that satisfies the equation above. Thus the strips all add and also produce a beam at that angle. Thus, the grating obeys the same equation as two strip mirrors.

The important point here is that the angle θ , depends on λ. Thus, *different wavelength light will be bent through different angles.*



A GRATING is equivalent to many parallel mirror strips each the same distance, a, apart. It obeys the same equation as two mirror strips.

OPTIONAL EXPERIMENT:

Using the set-up you have used, measure θ for yellow light. Calculate a from the fact that the grating has 13,400 lines per inch. Then calculate the wavelength of yellow light. Careful measurements of this sort are the best way to determine wavelengths.

REVIEW

SUMMARY

In this and the preceding chapter you built a simple spectrophotometer and used it to make approximate *transmission spectra*. Since the key to spectrophotometers is the *dispersion element*, you then examined both the grating and prism in greater detail to understand what effect they have on light. You found that both break up white light into its component colors and arrange these in order of their *wavelengths*. With the grating there is a simple, straight line relationship between wavelength and the location of a given color. The prism on the other hand compresses the red end of the spectrum. The physics behind these two elements was briefly covered.

You learned how to assign numbers to colors. These numbers are based on the fact that light acts like waves. Colors as well as non-visible radiation can be named by their wavelengths. These wavelengths are short, so special units of length, including the *nanometer* and *Angstrom*, are used.

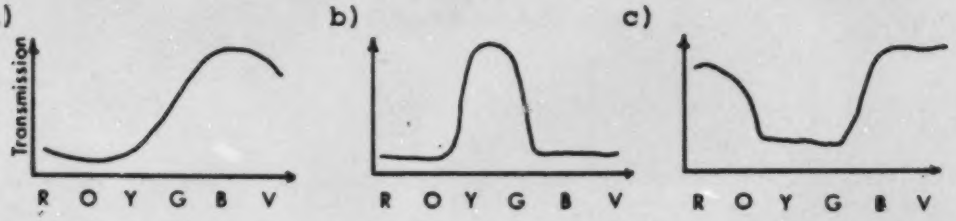
Our simple spectrophotometer is not accurate enough for practical use. Before building a more accurate one, we must learn some optics -- the first subject of the next chapter. After this you will build a better spectrophotometer and make an accurate transmission spectrum of a didymium filter.

QUESTIONS

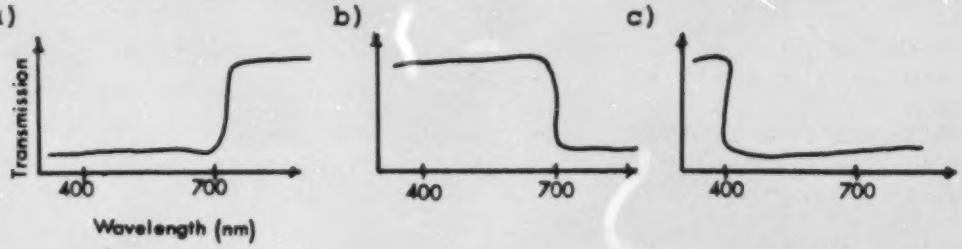
1. Which colors are always left in the spectrum by the following filters:

   a) Yellow? b) Red? c) Orange?

2. What color filters would give the following transmission spectra?



3. Which of the following transmission spectra belong to a filter which stops infrared radiation?



4. Look at the commercial spectrophotometer on page . Identify each of the five basic components in it.

5. Which of the colors in the spectrum covers the largest range of wavelengths? Which covers the smallest wavelength range?

6. What determines the order of colors in a spectrum?

7. Is blue light bent less or more than red by a prism? by a grating? Why?

8. Does either the prism or the grating have approximately *constant* dispersion? (Look at your data) Which?

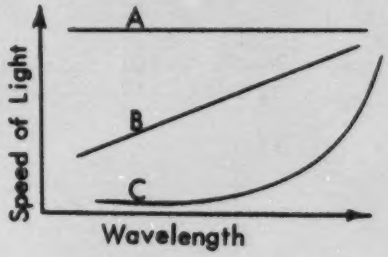
9. Why is the dispersion of a prism not constant?

10. Which dispersive element has the greater over-all dispersion?

11. For what colors are the dispersions of the prism and grating approximately equal?

12. Which of the graphs on page 36 might be from a grating? How would this grating differ from yours in terms of dispersion? Which would be better to use to obtain the widest spectrum?

13. Suppose that there were substances A, B & C that had speed of light/wavelength dependences as shown at right. If prisms were made from each substance, how would they disperse the light?



14. Why are small values of resolution desirable?

15. Why can't you resolve pure colors when the images of their entrance slits overlap?

PROBLEMS

1. What are the five basic components in ever spectrophotometer?

2. Describe each of the spectrophotometer components used in the first experiment.

3. What are the limits to the wavelength range of both prisms and gratings? What is the physics behind these limits?

4. Draw a diagram of the electromagnetic spectrum showing the range of wavelength for the infrared, visible and ultraviolet and describe the properties of each type of radiation.

5. Describe why four important characteristics of light (reflection, refraction, interference and diffraction) are consistent with a wave model for light.

6. Convert the following wavelengths to nanometers (nm):

   a) 3580Å b) .64μ c) 481mμ

   d) 4.3×10^{-7}m e) 1.7×10^{-5}cm f) 358.41nm

7. Convert 431 nm to:

   a) Angstroms b) μ c) cm d) m e) mμ

8. The entire visible spectrum is in the range from 400nm to 700nm. What is this range expressed in:

   a) Angstroms? b) frequency?

   c) wavenumbers? d) meters?

9. What color is each of the following?

   a) 450nm b) $19{,}000 cm^{-1}$

   c) $5 \times 10^{14} Hz$ d) $6.75 \times 10^{-5} cm$

10. How many wavelengths of red light fit into a centimeter?

11. Which dispersive element that you measured had the best (i.e., smallest) resolution? For which wavelength?

12. Which element had constant resolution? Why?

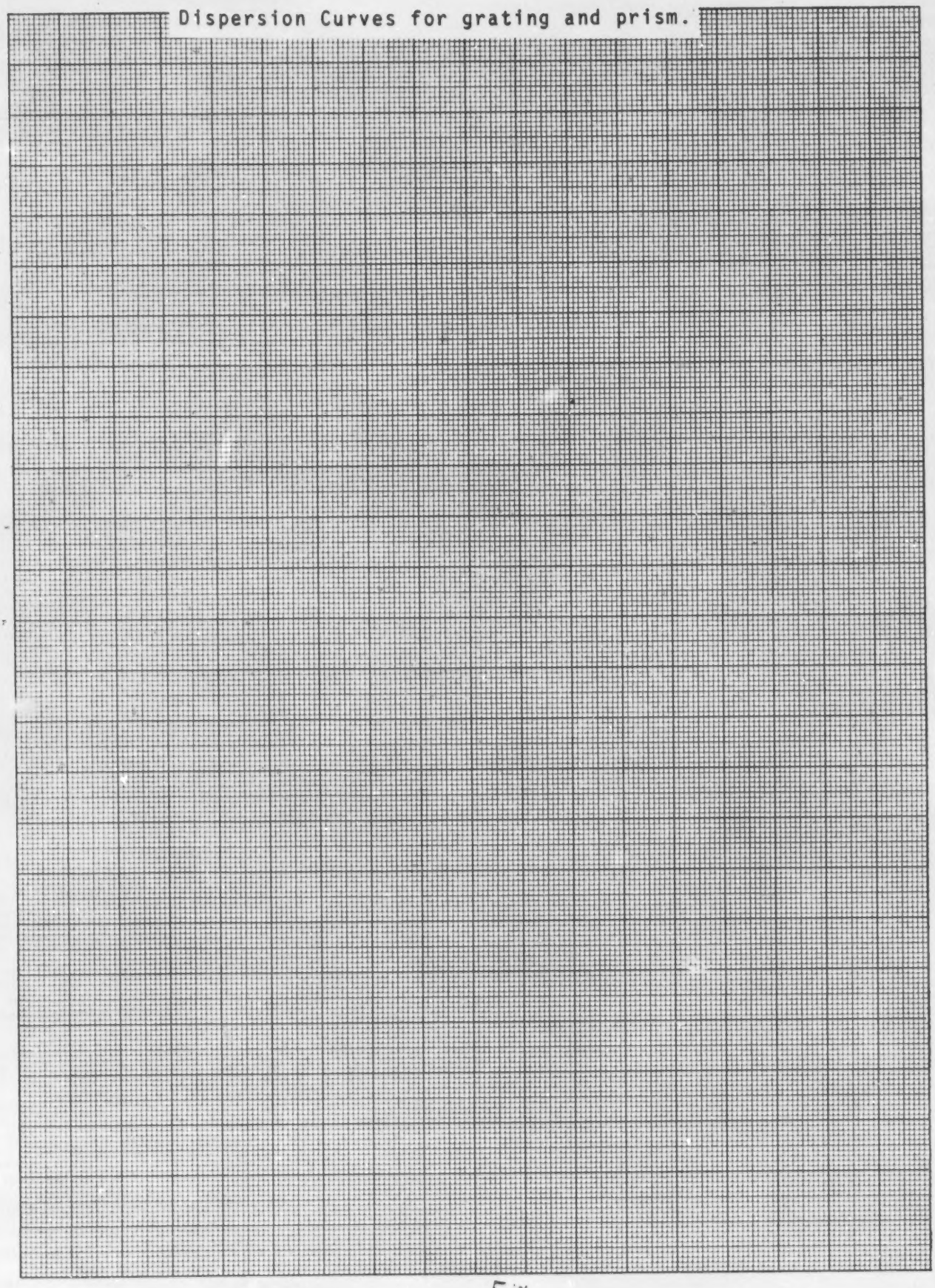
13. What determines the useful range of prisms & gratings?

Table of distance versus color for the spectra produced by a grating and a prism.

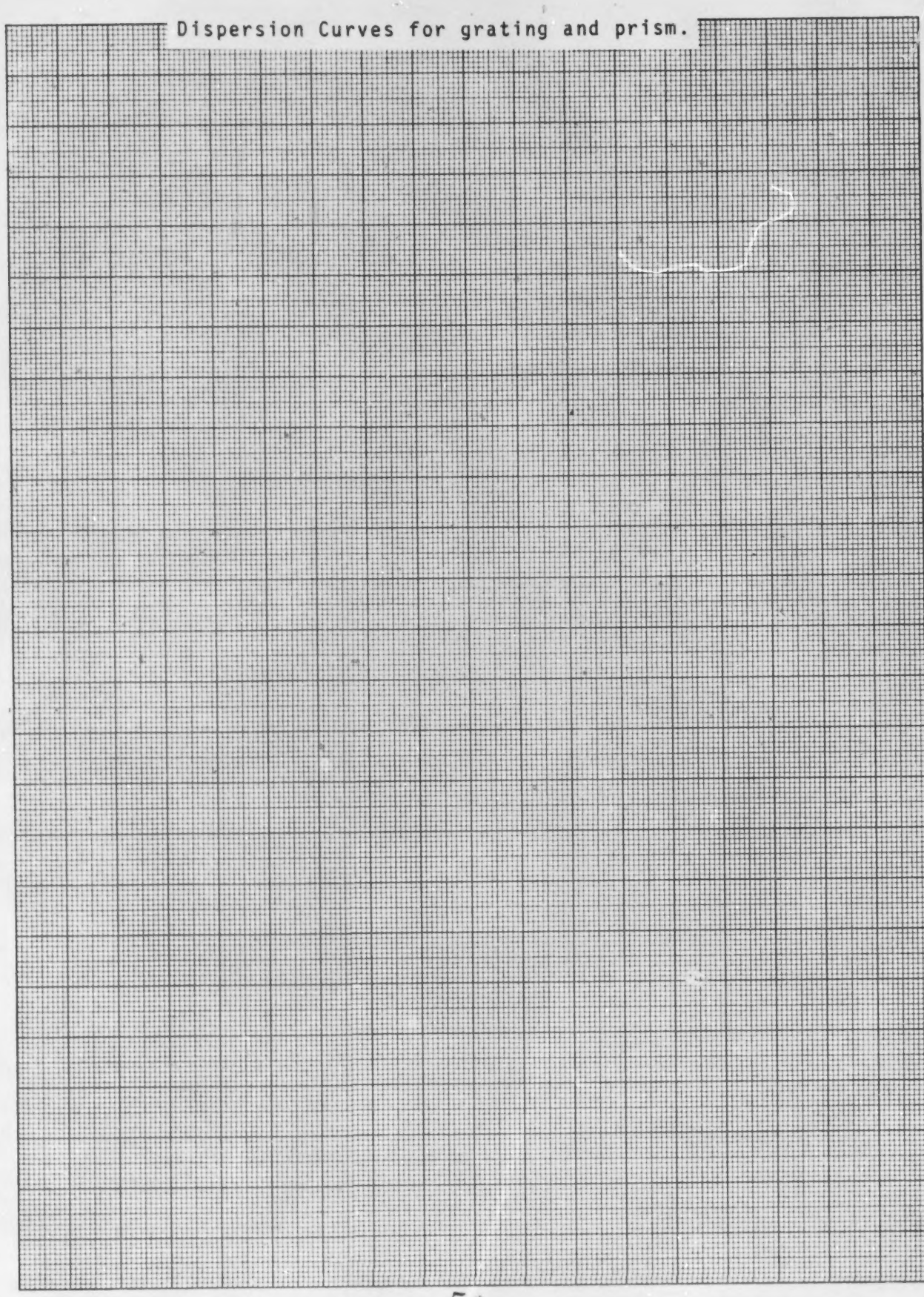
Table comparing the dispersive properties of a grating and a prism.

Resolution of the prism and grating at wavelengths of 400, 550, and 700 nm.

Dispersion Curves for grating and prism.



Dispersion Curves for grating and prism.



SPECTROPHOTOMETER ANALYSIS

INTRODUCTION

So far we have concentrated on prisms and gratings. We now ask how they are used in spectrophotometer systems to produce good quality spectra. We will use these ideas to make a better spectrophotometer. And when we understand how the system works, we will ask the more important question, *how well* does a given system work.

A monochromator is designed around the dispersive element - the prism or grating. In essence every monochromator uses a dispersive element to make a spectrum. Once you have the spectrum, you can get pure colors by letting part of the spectrum through the exit slit. All the optics before this is designed to project a high quality, intense spectrum onto the exit slit.

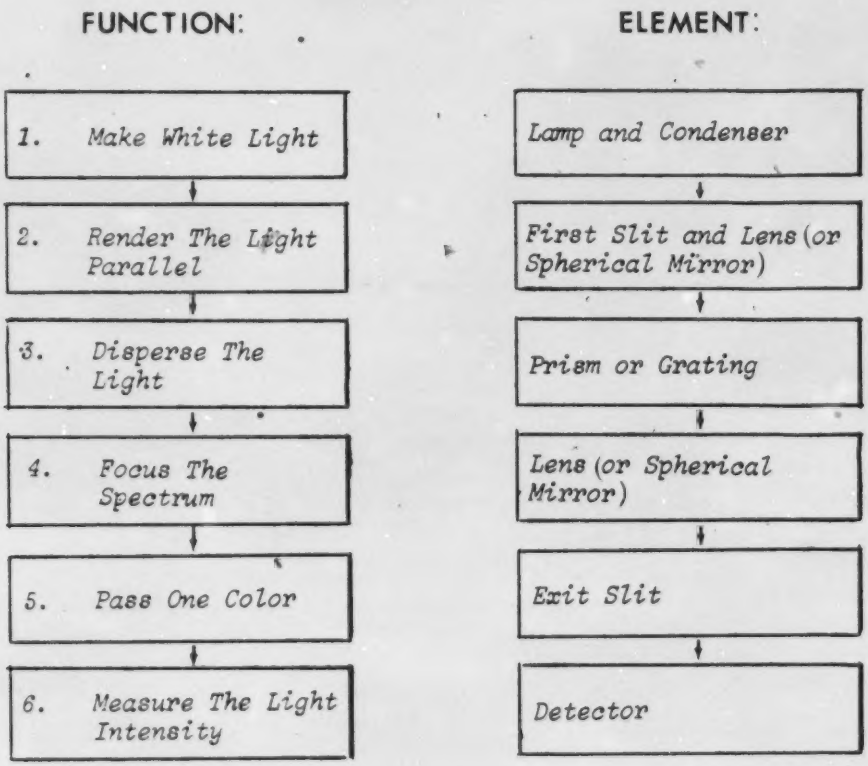
You may be puzzled because this is a module on the spectrophotometer and yet we seem to be most interested in monochromators. The point is that for our purposes there really isn't much difference between the two. A spectrophotometer is essentially a monochromator with a light source hung on one end and a sample and light detecting system hung on the other end. Other modules concentrate more on these other elements of a spectrophotometer.

WHY THE OPTICS?

HOW DO YOU MAKE A GOOD SPECTRUM?

Because of effects we have neglected, both prisms and gratings work best with parallel light. So most monochromators start by making parallel light using a slit and either a lens or a spherical mirror. This makes parallel light for the dispersive element. Since parallel light comes in to the dispersive element, parallel light will also come out. Thus, another lens or spherical mirror is used to focus this parallel light. The exit slit is placed at this focus.

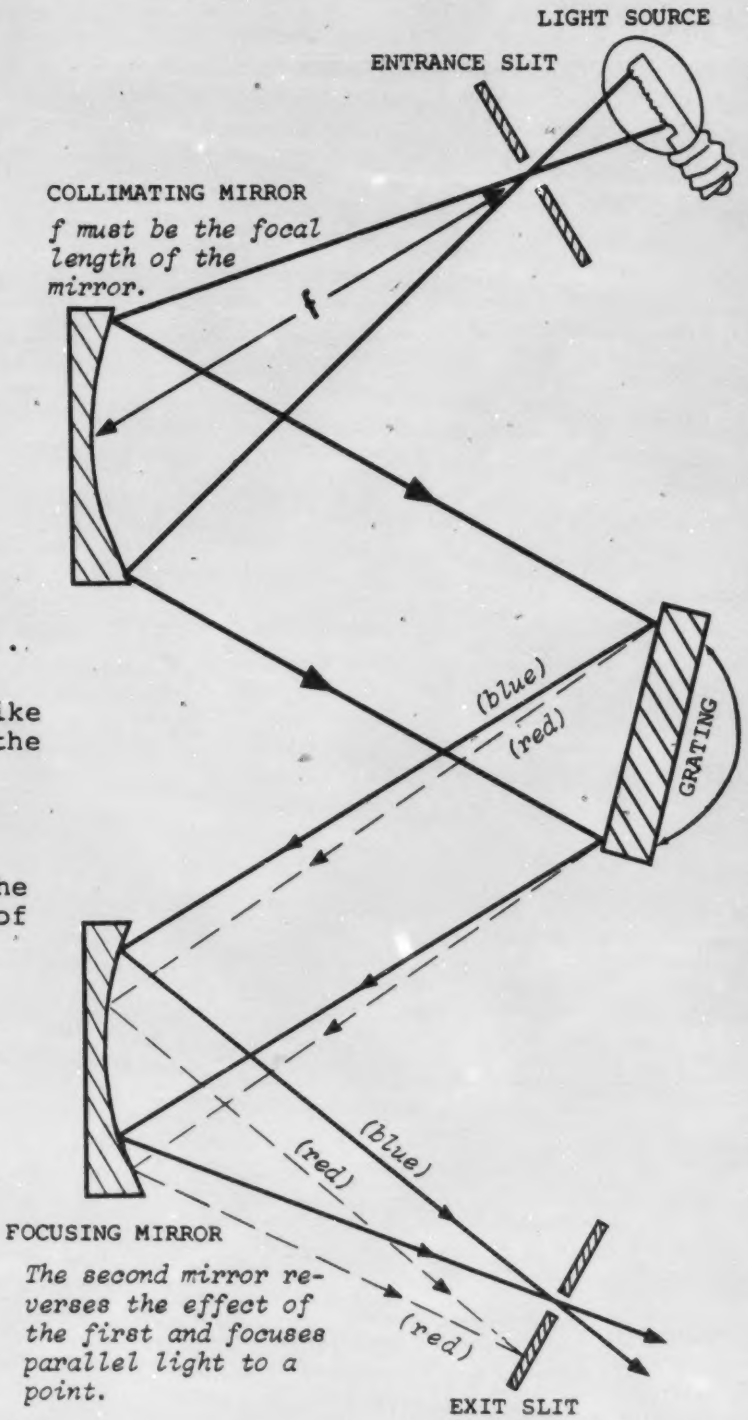
The block diagram below summarizes the essential functions within almost every spectrophotometer:



SYSTEM FUNCTIONS found in almost every spectrophotometer. The first four steps spread light out into a spectrum, and the fifth stops all but a small and almost pure part of that spectrum.

THE ESSENTIALS OF A MONOCHROMATOR

The system functions outlined on the previous page can be seen in operation in the schematic diagram below.



The purpose of the first mirror is to take white light which diverges from the first slit...

...and render it parallel....

...so that it will all strike the grating (or prism) at the same angle.

Different colors come off at different angles from the grating but all the light of a given color is parallel.

The paths of red & blue light from the grating are shown opposite.

Only when the second mirror is focused on the exit slit will the parallel light be focused there...

...different points on the exit slit for different colors.

All the light except blue is blocked by the exit slit.

Moving the slit or rotating the grating would let other colors through.

VARIATIONS ON A THEME

A LENS MONOCHROMATOR

The schematic diagram on the previous page is not the only way to produce a good spectrum. If lenses are substituted for spherical mirrors you get a monochromator like the one on the opposite page. Other variations would result from substituting a prism for the grating. Diagrams of prism monochromators are found later in the module. Other variants will also be discussed. The important point, though, is that *they all need to use parallel light.*

A WORD ABOUT LENSES & SPHERICAL MIRRORS

You don't need a thorough grounding in optics to understand the use of lenses and spherical mirrors in monochromators. Lenses and spherical mirrors are both found in monochromators because they both perform the same two tasks. They both can do the following:

Collimation: Collimating the light coming from the first slit, simply means making the light beam parallel;

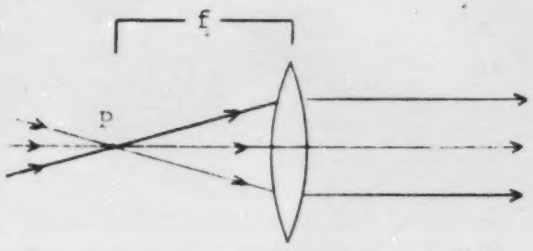
Focusing: Focusing the parallel light coming from the grating or prism to a point on the exit slit.

The sketches below show both a lens and a spherical mirror doing each task: *in each illustration f represents the focal length of the lens or mirror and P respresents the position of the slit.*

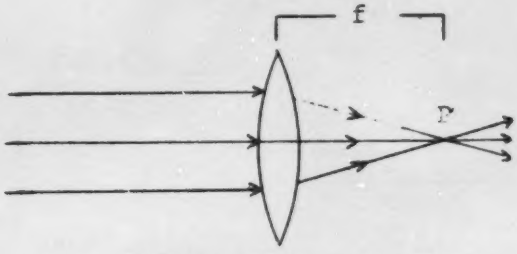
COLLIMATION

LENSES

FOCUSING

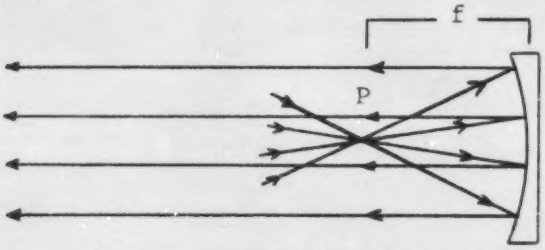


Light diverging from a point P a distance f behind the lens emerges parallel.

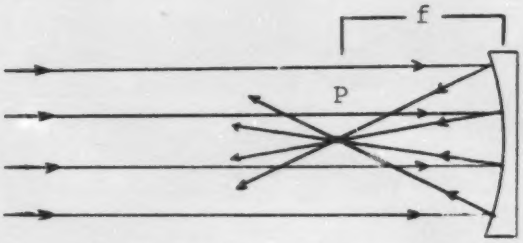


Parallel light is focused to a point P at a distance f from the lens.

SPHERICAL MIRRORS



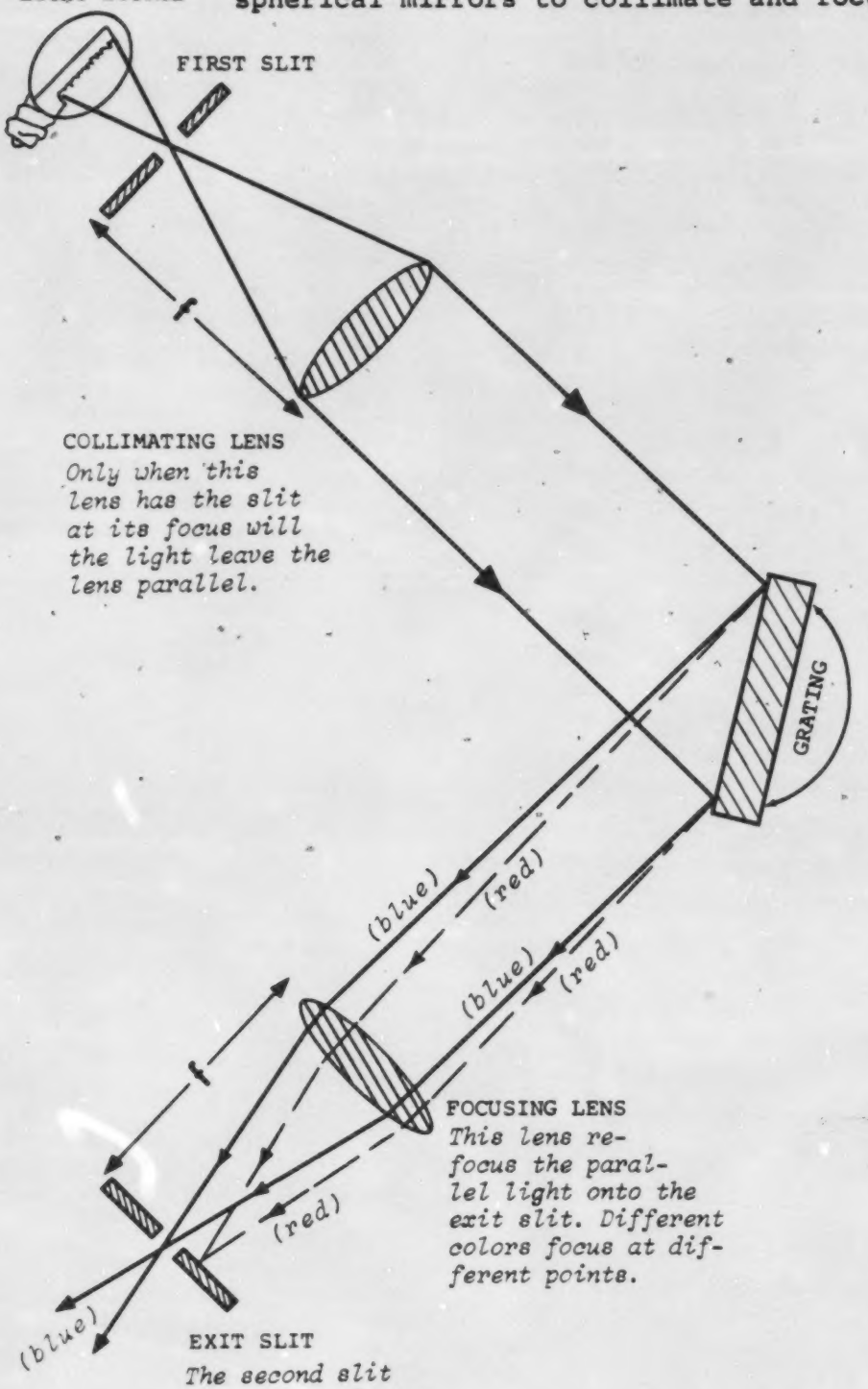
Light diverging from a point P a distance f in front of the spherical mirror emerges parallel.



Parallel light is focused to a point P at a distance f from the spherical mirror.

LENSES CAN BE USED INSTEAD OF SPHERICAL MIRRORS

The illustration below shows a monochromator identical to that on page 51 except that lenses are used instead of spherical mirrors to collimate and focus the light.



The purpose of the first lens is to take the white light which naturally diverges from the first slit...

...and render it parallel...

...so that it will all strike the diffraction grating (or prism) at the same angle.

Here different colors come off at different angles.

All the light of a single color is parallel.

So the second lens reverses the first and focuses this parallel light at different points on the exit slit for different colors.

AN EXPERIMENT TO BUILD A BETTER SPECTROPHOTOMETER

INTRODUCTION

Our objective is to understand how well spectrophotometer systems work. The best way to get at this is to build the best spectrophotometer system we can. We will then use this system and determine from experiences what the short comings and limitations are. While better systems can be built, they too will be subject to limitations, as we will discover. The next four pages describe in detail how to set up the student spectrophotometer. Following that are two pages that describe one of many possible experiments that we could perform with this instrument. In order for this spectrophotometer to be really useful, it is necessary to be able to measure the wavelength of any light that may go through it. To determine which settings on the instrument correspond to which wavelength, we need to *calibrate* the spectrophotometer. The calibration procedure is explained in the last two pages of the experiment.

Care and patience is required in this laboratory because every step must be performed accurately before going on to the next. Otherwise your errors will accumulate, and you will not have an accurate instrument.

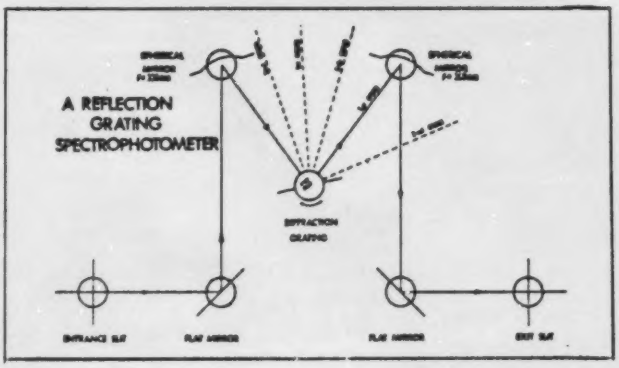
PROCEDURE

Obtain the template titled REFLECTION GRATING SPECTROPHOTOMETER (shown below) and tape it securely to the monochromator box. (Your instructor may ask you to set up a different monochromator system and will provide you with the proper template).

The alignment steps are separated into four phases.

I - FOCUSING THE LIGHT SOURCE
II - ALIGNING THE MONOCHROMATOR
III - ILLUMINATING THE PHOTODETECTOR
IV - ADJUSTING THE AMPLIFIER

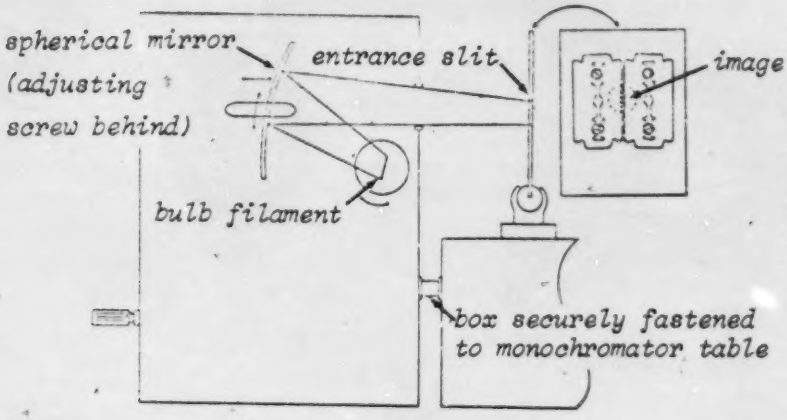
Follow these steps carefully to obtain an accurate alignment of your spectrophotometer system. If you are using an optical monochromator system different from that shown you will have to modify the steps of phase II.



The layout of components for the reflection grating spectrophotometer.

I. FOCUSING THE LIGHT SOURCE

OBJECTIVES: The purpose of the light source is to provide a high intensity source of white light for the monochromator. To do this a spherical mirror is used to gather as much of the output of the bulb as possible and concentrate it on the entrance slit. In practice this means to form an image of the bulb filament that just fills the entrance slit. This is your objective in aligning the light source box. The following steps and the diagram below may help you.



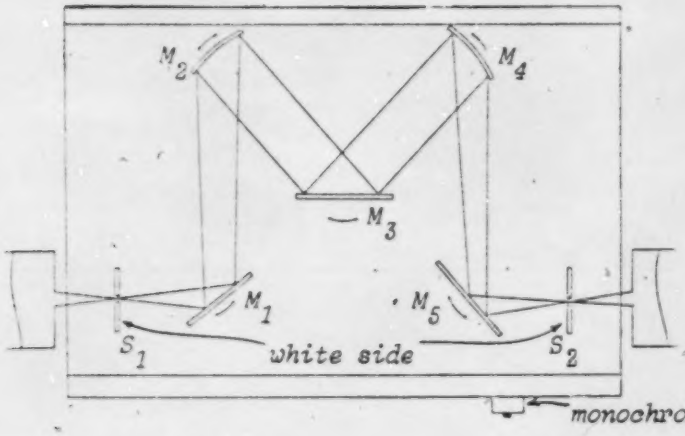
THE LIGHT SOURCE. The bulb and mirror must be adjusted to throw the largest possible amount of light on the slit. This occurs when an image of the filament is focused on the slit.

1. SETTING UP: *Open the light source box* and observe the general arrangement. By loosening the screw in the back you can change the *position* and the *angle* of the spherical mirror. You can also rotate the filament. Be sure the entrance slit is properly positioned on the monochromator table, with its *white side toward the light.*

2. IMAGING THE FILAMENT (Coarse): *Turn on the light source* but be careful not to look at the filament for very long since it is quite bright. Keep your eye on the entrance slit as you try to image the filament.
   Rotate the mirror and move it back and forth until you have a good image of the filament on the entrance slit.
   Rotate the filament and observe what happens to the image. Leave it where you get the sharpest image (roughly what you see in the diagram).
   Turn the entrance slit around (black side to light source) when you have achieved the best image with the mirror.
3. FINE ADJUSTMENT: *Move the slit back and forth* until again you get the best image. If you have to move it more than 1/4" from its initial position you should go back and readjust the mirror.
   Place a white card centered on the line after the entrance slit and observe the light coming from the slit. Make fine adjustments of the slit until the image is centered, bright and uniform on the card.
   Close the light source cover.

II. ALIGNING THE MONOCHROMATOR

OBJECTIVES: The purpose of the monochromator is to disperse the white light from the source into its component colors in such a way that the operator can select any one of them to exit to the sample. The mirrors (flat and spherical) are used to get the colors pure and concentrated on the exit slit. A simple way to achieve the proper mirror alignment is to replace the dispersive element with a flat mirror, and then to form an image of the entrance slit on the exit slit. When you put the dispersive element back, your optics should be in good alignment. This is your objective here and again the diagram and steps below may provide a guide.



THE MONOCHROMATOR. The template showing the positions of components should be taped securely to the box. Each component, starting with S_1, must be adjusted to pass the maximum light squarely on to the next.

1. SETTING UP: *Place the components* in their proper positions on the monochromator table, putting a flat mirror in place of the grating. Have the white side of the exit slit facing inward. Each component can be *rotated* to direct the light to the next component and *tilted* to be sure the light travels parallel to the base.

2. IMAGING THE ENTRANCE SLIT (Coarse): For aligning the components use a white card to trace the light path. Be sure the light beam is centered both horizontally and vertically at each step.

   First place the card in front of the spherical mirror M_2, (centered on the light path line) and rotate and tilt M_1 until the light spot is centered on the card.

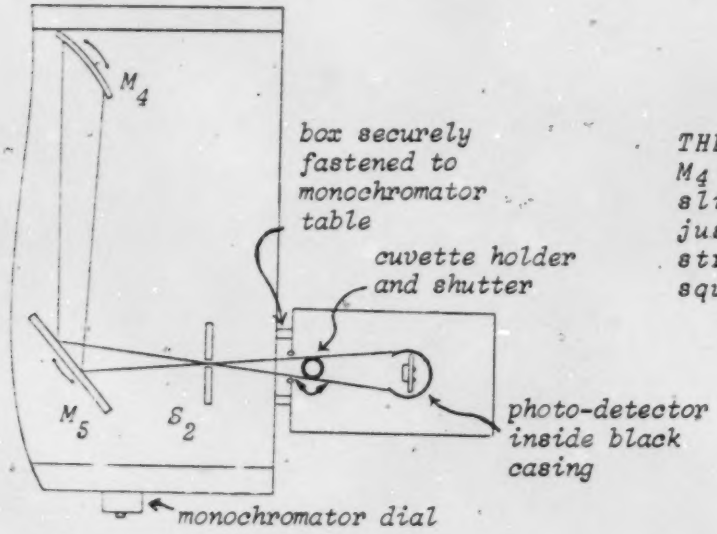
   Next place the card in front of M_3 and *spherical mirror* M_2. Continue this process from component to component until an image of the entrance slit appears on the exit slit. Be sure each component remains near its designated spot.

3. FINE ADJUSTMENT: A fine adjustment of the system may be made by moving the exit slit back and forth until the smallest (and brightest) image appears on the exit slit. If the system is perfectly aligned, the image of the entrance slit should exactly match the size and shape of the exit slit and all of the light will pass through.

   Close the monochromator top and introduce smoke into the chamber, and compare your light path with the diagram.

III. ILLUMINATING THE PHOTO-DETECTOR

OBJECTIVES: You have now set up most of the optical components in the spectrophotometer. However, the photometer part of the spectrophotometer is still missing. Your strategy here is to get the maximum amount of light falling on the photo-detector. This may require some fiddling with the mirrors 4 & 5 and slit 2. The final proof of your ability to get light into the photo-detector will be the amplifier and meter which essentially measures the current produced by the photo-detector. There should be enough light on your photo-detector to cause the amplifier to read full scale throughout the visible spectrum and well into the infrared.



THE PHOTO-DETECTOR. Mirrors M_4 and M_5 as well as the slit S_2 may have to be adjusted to have the light strike the photo-detector squarely.

1. SETTING UP: *Open the detector box* and remove the cuvette holder.

2. FLOODING THE PHOTO-DETECTOR: If the light does not fall squarely on the photo-detector, *rotate mirrors M_4 and M_5 together*, changing the angle of incidence of the image on the exit slit until the detector is uniformly lighted.

   Replace the cuvette holder when this is done. Rotate it and note how it acts as a shutter. With the shutter open, the detector inside the housing should be brightly lighted.

3. ADJUSTING THE GRATING: *Replace the mirror M_3* on the turn table with the diffraction grating.

   Rotate it so that the 0th order (white light) falls on M_4 producing an image of the entrance slit on the exit slit.

   Tilt the grating so that the image is centered on the exit slit. Make a fine adjustment to produce the best image by moving S_2 back and forth.

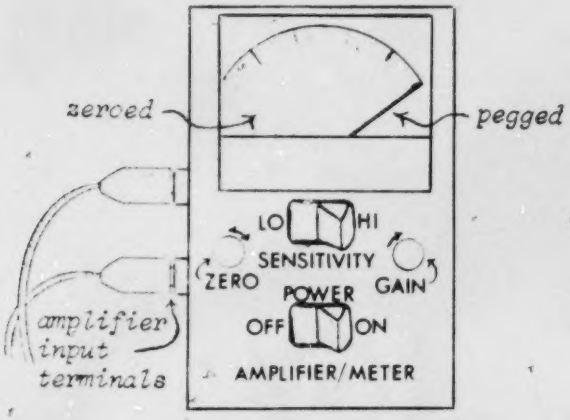
   Does the light still fall squarely on the detector?

   Rotate the grating counter-clockwise until the 1st order spectrum falls on the exit slit. Be sure that as you scan the colors, each fully illuminates the exit slit and strikes the photo-detector as it passes.

   Close the detector box and introduce smoke into the chamber. How well are your components aligned?

IV. ADJUSTING THE AMPLIFIER

OBJECTIVES: With the monochromator set up and the system properly aligned, it is important that the electronics be operating properly and that the system has sufficient wavelength range for your measurement. Your objective here is to properly adjust the amplifier and meter and to set the dial and position the grating for the measurement.

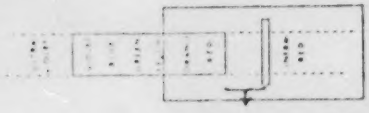


THE METER should be able to register a full scale deflection throughout the visible and well into the infrared.

1. ADJUSTING THE METER: *Plug the meter* into the black and blue terminals of the detector box, being careful not to bump the monochromator.
   Close the shutter and turn on the meter.
   Adjust the Zero Set to read 0 on the scale with the Gain turned all the way up.
   Open the shutter and the needle should peg at 100%. If it goes in the other direction, the meter is probably plugged in backwards. Reverse the terminals.

2. CHECKING THE RANGE: *Rotate the grating* back and forth to scan the spectrum by the exit slit. The meter should stay pegged from well into the blue to at least a half inch into the infrared. If it doesn't, either the batteries in the detector are low or your optical alignment is not good. Have your instructor check this out with you. The *Range* of your instrument is determined by the range of wavelengths (from ultraviolet to infrared) over which your detection system will register 100%.

3. SETTING THE DIAL AND GRATING BY HAND: *Set the monochromator dial* to read zero.
   Rotate the grating so that at least 1/2 inch of the infrared can be scanned by the monochromator as shown below.
   Close the monochromator cover.



THE SPECTRUM ON THE SLIT should look like this when the monochromator dial is set at zero.

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Turn the dial to scan the spectrum past the slit. Be sure that you go at least to the violet/ultraviolet boundary. If the dial reaches the end, turn the grating by hand so that the boundary is to the right of the slit.
Return the spectrum to its original position with the dial so that the dial reads zero and the spectrum is positioned as shown.
Close the monochromator cover. You are now ready to make a measurement.

AN EXPERIMENT USING YOUR SPECTROPHOTOMETER:

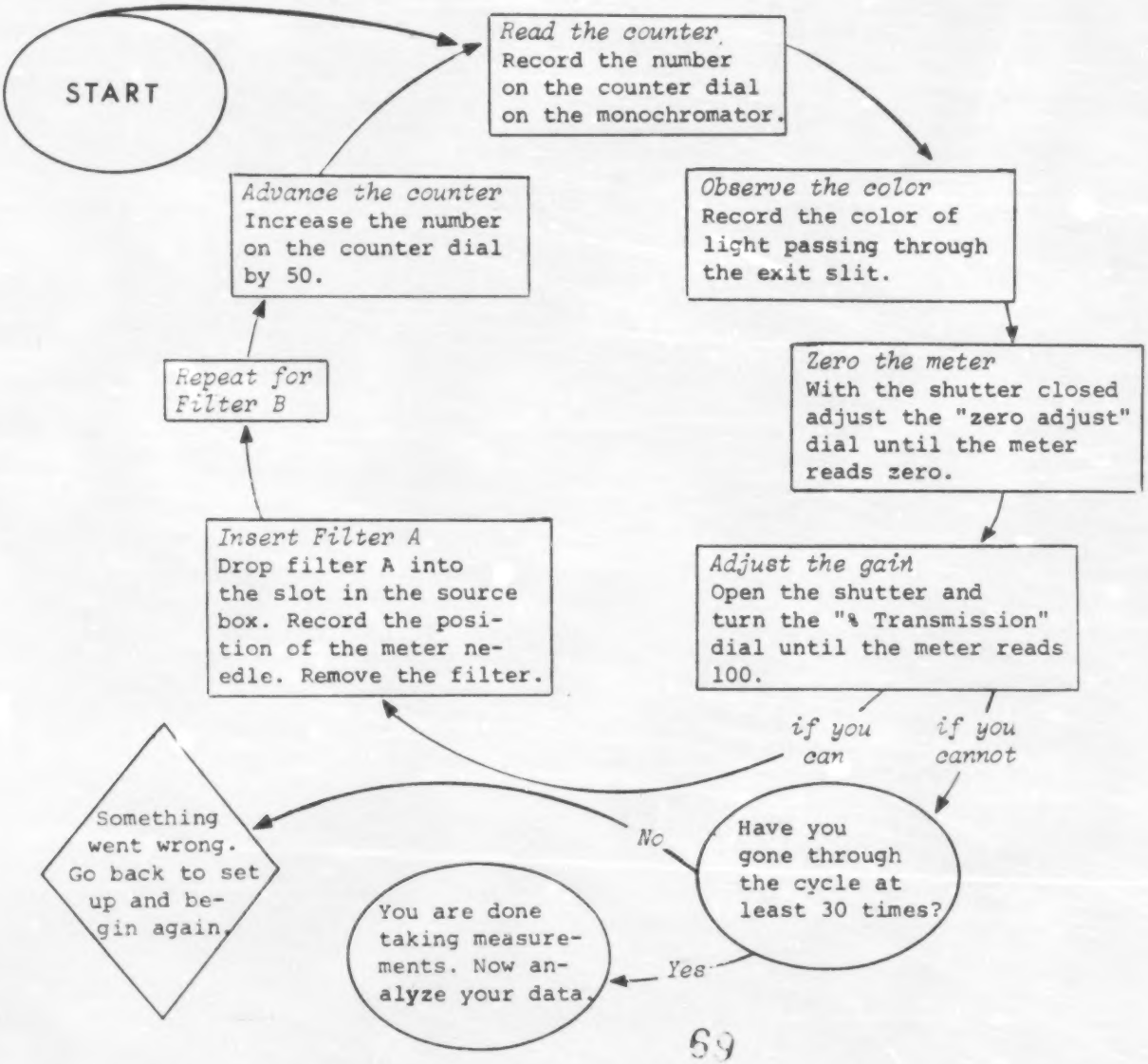
INTRODUCTION

We will use our spectrophotometer for a simple experiment which illustrates the value of these instruments.

In this experiment the spectrophotometer extends our senses in two ways. First, it can measure large differences in two filters, which appear to be almost the same. Secondly, it measures the "color" of the filters beyond the range of our eye. The two filters to be used in this experiment are:

A. The didymium filter,
B. Filter #849, a pale blue filter that looks almost identical to the didymium filter.

PROCEDURE: Follow the steps in the flow diagram below to obtain your data. On the following page is a sample data table for this experiment. Use the designated page at the end of this section for your data table.


START
Read the counter
Record the number on the counter dial on the monochromator.
Observe the color
Record the color of light passing through the exit slit.
Zero the meter
With the shutter closed adjust the "zero adjust" dial until the meter reads zero.
Adjust the gain
Open the shutter and turn the "% Transmission" dial until the meter reads 100.
if you can
if you cannot
Have you gone through the cycle at least 30 times?
No
Yes
Something went wrong. Go back to set up and begin again.
You are done taking measurements. Now analyze your data.
Insert Filter A
Drop filter A into the slot in the source box. Record the position of the meter needle. Remove the filter.
Repeat for Filter B
Advance the counter
Increase the number on the counter dial by 50.

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THE FLOW DIAGRAM above outlines the basic steps in taking data for the spectrum of two filters, labeled A and B.

ANALYZING YOUR DATA

The numbers recorded for the filters are the percent of light transmitted at each different color. The way we adjusted the meter, if no light were absorbed, the meter would read 100 -- meaning 100% was transmitted. Similarly, if the meter read 0, it would be the same as totally blocking the light with the shutter indicating 0% was transmitted. If the meter read 50, half the light would be absorbed, half, or 50%, transmitted.

So, without any work, you can look at the numbers and see that while the two filters may look similar to the eye, they are not the same. This means that the spectrophotometer has measured *quantitatively* differences between the two. To demonstrate the differences more clearly, graph the % transmission for the two filters against dial reading as illustrated below. This graph is called a *Transmission Spectrum*. Use the graph paper at the the end of this section for your transmission spectrum.

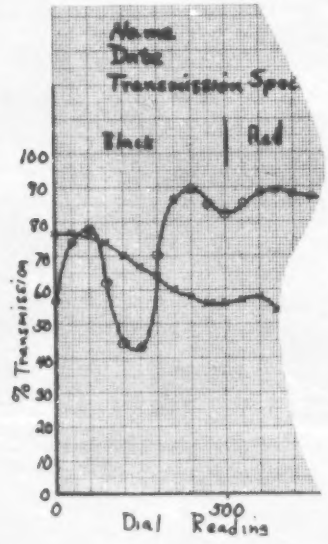
From the graph, answer the following questions:

What color does each of the filters transmit most? Is this exactly the color of the filters when you simply look at them? What color would a blue filter transmit most?

Dial Reading	Color	% Transmission Didymium	% Transmission #849
0	Black	57	77
500	Red edge	82	56
550		85	57
600		88	58
650		89	52 54
700	Red center	88	51
750		87	
800			
850			
900			

POSSIBLE DATA shown as a student might have recorded it.

What color has the greatest difference in transmission between the two? Why doesn't this affect the color that the filters appear to be?....Or does it?



TRANSMISSION SPECTRA for two (!) seemingly similar, but quite different, filters.

OPTIONAL EXPERIMENTS

1. Several additional filters are supplied. Guess the transmission spectrum of each and then measure it, repeating the procedure above.

2. Transparent objects simply do not absorb the light we can see. However, the spectrophotometer can measure absorption beyond the visible. Find some transparent materials --plastic, cellophane, glass-- and measure their transmission spectra. Obtain thick samples for the greatest effect. Cellophane can be made thick by folding many layers together.

3. Sunglasses are common filters. One extremely important function of sunglasses is to cut out harmful ultraviolet. Obtain a pair of sunglasses and see if they do indeed cut out ultraviolet.

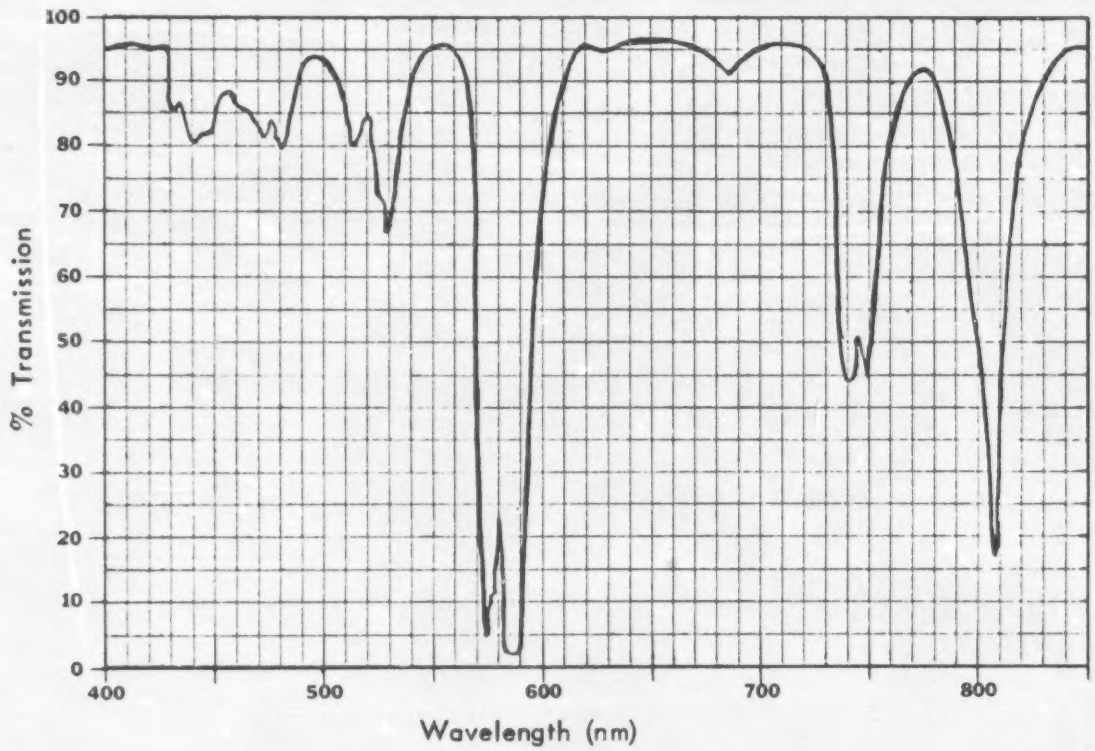
CALIBRATING THE SPECTROPHOTOMETER

INTRODUCTION

We have stated that we shall use nanometers to measure light. But how is it done? How do you determine the precise wavelength in nanometers of the light being detected in the spectrophotometer?

We measured the wavelength in dial settings. The process of determining the relation between dial settings and wavelengths is called *calibration*. The simplest method of calibration is to find sharp features on a known spectrum. For instance, sunlight has a sharp dip at 527 nm, and yellow in a flame has a sharp peak at 589 nm.

One of the filters you used in the experiment is called a *didymium filter* and is often used for spectrophotometer calibration. It has several sharp drops and peaks whose wavelength is known exactly. So, you have already done most of the work involved in calibrating the spectrophotometer. Compare your spectrum for the didymium filter to the spectrum below obtained using a commercial spectrophotometer. *Note that the two curves are mirror images of each other!*



Transmission Spectrum of Didymium Glass Filter as taken from a Beckman DU Spectrophotometer.

FINDING THE CALIBRATION POINTS

The spectrum is like a finger print which has several key identification points. The wavelengths of these key points are already known so you can use them to find the wavelength of your spectrum. You should see at least the following identifying points:

1) The large valley in the yellow, which is centered at 580 nm.

2) The peak on the green side of the large valley which occurs at 555 nm.

3) The dip in the far red, centered at 685 nm.

4) The dip in the infrared at 740 nm.

Compare your didymium spectrum with the one shown and see if you can see these points. What additional points can you identify?

DRAWING THE CALIBRATION GRAPH---

The purpose of calibration is to be able to translate dial settings into nanometers. This will be done by drawing a graph called a *calibration graph*. This is a graph of dial setting against wavelength in nanometers. It, therefore, immediately gives the values of wavelength in nanometers for any dial setting. The graph is constructed from the key identification points on the didymium filter.

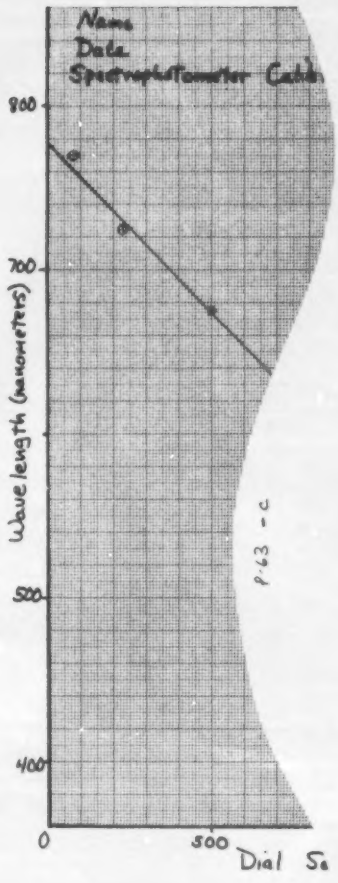
An Example: Let us work through an example of calibration so you can calibrate your readings.

1. *Make a table* like the one on the next page. Use the designated page at the end of this section for your graph. This shows the dial readings from the spectrum for each of the known key features of the didymium spectrum. You should be able to identify at least 8 features.
2. *Graph the dial settings* against the wavelengths as shown. Use the graph paper at the end of this section.
3. *Draw a straight line* through the points that gets the closest possible to all the points.

You can now read the value in Angstroms for any dial setting. For instance, the graph shows that dial setting 700 corresponds to 654 nm.

Feature	Dial Reading	Wavelength (nm)
large valley	230	740
Peak	400	710
slight dip	500	685
large valley	975	580

Table of dial readings at which key features of your didymium spectrum appear. Comparing your spectrum with the published spectrum lets you determine the exact wavelength of these features. From the table a calibration graph for your spectrophotometer can then be drawn.



RECALIBRATION: If you want to set up this same spectrophotometer again at a later time you can use your results here to calibrate it more quickly the second time. You only have to use a single feature on the didymium filter to recalibrate.

Here's how it works: Suppose you wanted to use the big dip in the spectrum at yellow in the example above. You would then set the dial at 970 and then rotate the grating, on its base, by hand until that feature was on the exit slit. You could determine when the feature was exactly on the slit first by eye but then by using the meter and amplifier attached to the photo-detector. If you do this all correctly, then each of the other key features should appear at the dial settings observed when you first calibrated the spectrophotometer. For instance, the dip at 685 nm should then occur at 500, the peak at 710 nm; at 400 and so on.

A REVIEW OF YOUR EXPERIMENT: WHAT HAVE YOU DONE?

USEFULNESS....TWO MAJOR APPLICATIONS

You have obtained the transmission spectrum for each of two filters. So what? What good are they?

Look at your two spectra and compare them to the way the two filters look. Although the filters look similar to the eye, the spectra are quite different. In particular, the spectrum for the didymium filter has a very unique and complicated pattern. These spectra are somewhat like fingerprints. There are catalogues of thousands of these spectra taken from all kinds of filters and liquids and each spectrum is unique and distinguishable. Thus, if you did not know your filter was didymium you could have gone to one of these catalogues and found it there, and unambiguously identified your filter.

QUALITATIVE ANALYSIS...

Thus, one of the most important applications of spectrometers is in identifying substances by means of their transmission spectra. Extending this idea you can see that it is possible to identify one substance in the presence of several others. Thus, for example, it is possible to identify small amounts of sodium dissolved in a complicated liquid, such as beer. This can be done because sodium has a unique absorbtion spectrum.

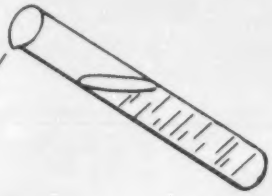
The gas helium was first discovered on the sun using spectral analysis. Before anyone had ever found this gas on earth, scientists knew its spectrum. Looking at the sun, they found the spectrum there. Thus, this gas was given the Greek name for the sun - helios.

At this point your teacher could, in principle, mix together a solution of four or five different chemicals that you never heard of and give it to you and ask you to determine which chemicals were in the solution by means of their transmission spectrum. In practice, this identification would be extremely difficult. You would end up with a spectrum that had twenty or more peaks or valleys and you would not know which features of the spectrum were due to which compound. The situation would be somewhat like listening to five people speaking at once and trying to keep track of what each one was saying all the time. The moral is that qualitative analysis is useful but limited to identifying one or two unknowns at a time.

QUALITATIVE ANALYSIS

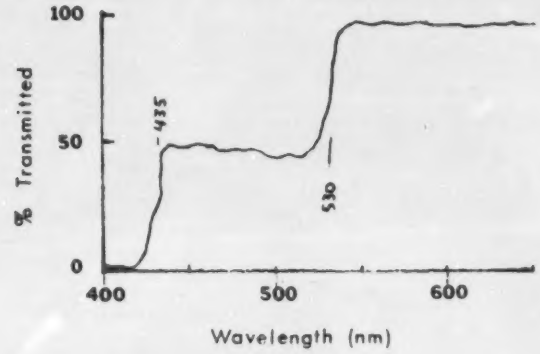
SUBSTANCE A

SUBSTANCE B

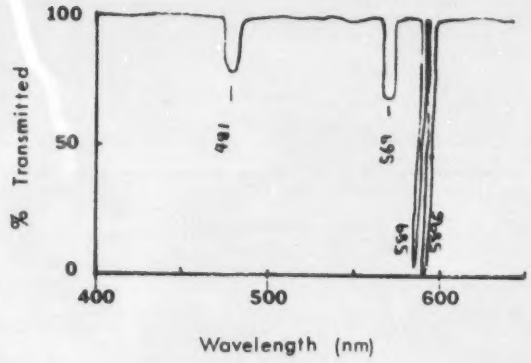


MIXTURE OF A & B

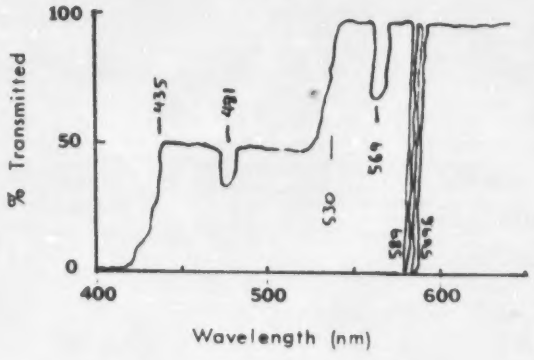
A's SPECTRUM:



B's SPECTRUM:



MIXTURE'S SPECTRUM:

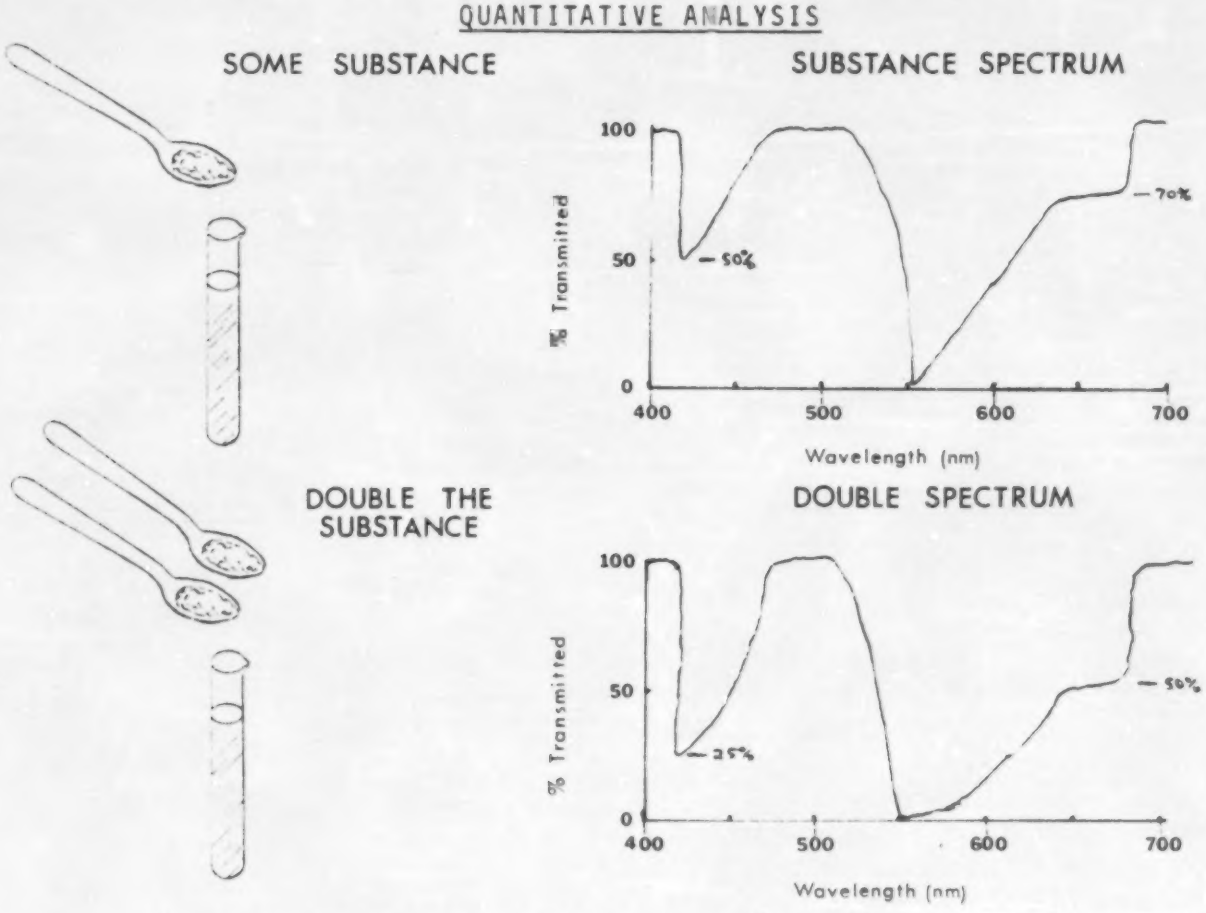


A spectrophotometer can be used to determine <u>what</u> is in an unknown substance. Each substance has its own unique spectrum, as suggested in the drawing above. Even when two substances are mixed the individual substances can be identified in the mixture's spectrum. For instance, A's two edges at 435 nm and 530 nm can be seen in the mixture's spectrum. Also the four absorbtion maxima from B at 481 nm, 569 nm, 589 nm and 589.6 nm can be seen in the mixture's spectrum.

QUANTITATIVE ANALYSIS...

One other important application of spectrophotometers is in finding out *how much* of each substance is present. You can well imagine that if we put two didymium filters together they would absorb twice as much light and each of the valleys would be twice as deep in your transmission spectrum. Similarily if you compare two solutions containing sodium, one with twice as much as the other, you can see that the one with twice as much sodium would absorb twice as much light.

This application is called *quantitative analysis* because you can determine the *quantity* of unknown substances that are present. This is extremely important in many chemical and medical applications. For instance, one can easily and quickly determine with great accuracy the amount of sugar in the blood of a diabetes victim from the spectrum of a very small sample of his blood.



A spectrophotometer can be used to determine how much of a substance is present. The more that is present, the more light it will absorb. By measuring the amount of light absorbed at a particular wavelength you can figure out the quantity of any substance that must be present.

In the top sketch, above, there is a valley at 420 nm representing 50% absorbtion. In the lower portion of the sketch, twice as much material is present in the same solution. Thus, an additional 50% of the 50% is absorbed, so that only 25% is transmitted at the 420 nm valley. Note that the locations of the spectral features are not changed, only their depth and shape.

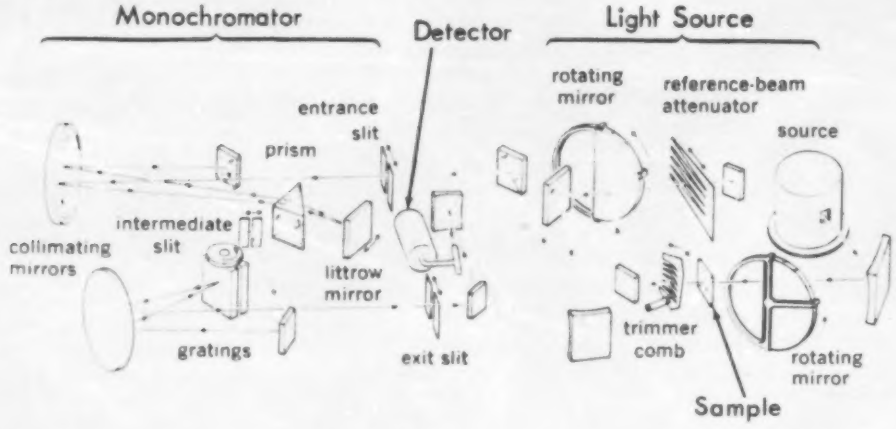
THEORY INTO PRACTICE....COMMERCIAL REFINEMENT

INTRODUCTION

Too often in your studies, what you learn about something in school is of little direct value when you face a real like problem. For instance, you may learn about combustion engines and still not know how to begin fixing your car. The problem is often that the real thing is too complex looking. All those added convenient gadgets - like power steering, pressurized cooling, electronic ignition, etc. - hide or conceal what you really know. All this complexity doesn't change how an engine works, it just makes it harder to see.

THE BECKMAN IR9 SPECTROPHOTOMETER

The same thing happens in commercial monochromators and spectrophotometers. Added gadgets make them easier to work, but hide the essential parts. However they cannot change the principles of operation we have developed in this module. For example, look at the complex instrument below. All those mirrors, lenses and motors make it hard to find the spectrophotometer. But it *is* there. Furthermore, we can find each of the functional elements mentioned on page at the begining of this chapter. These functional parts are identified in the drawing. This instrument has been made complex to make it easy to operate.



IR9 OPTICAL DIAGRAM - *This optical system uses both grating and prisms to disperse the light. It thus has very wide dispersion of the light and high resolution.*

Remember how much work you had to do to get a spectrum using the student spectrophotometer? All you have to do with this instrument is insert the sample, set some dials and turn it on. Out comes a graph of absorbtion or transmission.

This instrument uses two technological tricks - it sends light through two sample chambers (called "dual beams"), and uses feedback. These two tricks permit the following improvements: (1) no zero adjustments are required, (2) no full scale adjustments are required, and (3) graphs of transmission or absorption are automatically drawn.

The two beams are produced by switching the light from one path to the other. The circular objects in the illustration are half mirror and half clear. Rotating together, they alternate the beam between reference and sample.

The dual beam spectrophotometer uses feedback in the following way: It compares the output signal from the two beams. If the sample absorbs more light than the reference, then a signal is generated which turns on the motor which moves an attenuator, or comb, into the reference beam. As the comb moves in, it blocks more light until the reference and sample beams are of the same intensity. At this point, the attenuator is blocking an amount of light equal to the additional absorbtion in the sample over that of the reference.

AUTOMATIC GRAPHING

Since the amount of absorption in the attenuator depends on how far into the beam it is, all you have to do to get a measurement is measure where the attenuator is. This is most easily done by mechanically attaching a pen to it. As you change wavelengths (using a second motor to drive the Littrow mirror) the sample absorption will change. The attenuator will move in and out following these changes and the attached pen will draw the spectrum providing that you move the paper under it as you change wavelengths.

Since the output is essentially the location of the attenuator, no zero or full scale adjustments are needed. And since one can attach a pen to the attenuator, automatic graphing is possible. Thus, dual beams and feedback give the desired result.

(OPTIONAL)

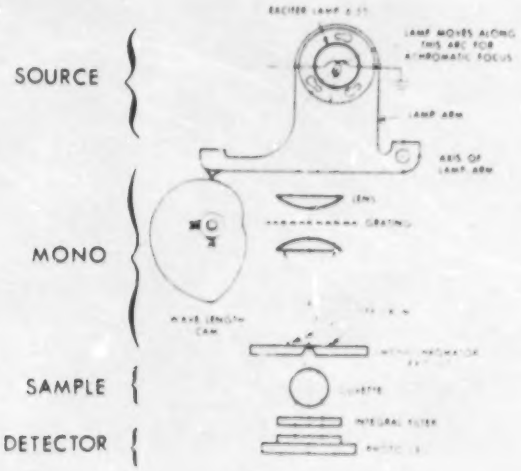
OTHER SPECTROPHOTOMETER SYSTEMS

INTRODUCTION

The spectrophotometer described in the main laboratory section is similar to many actual laboratory instruments. That particular arrangement of optical components is called the Czerny-Turner Mount. But you know that there are many other arrangements which can accomplish the same results. For instance, we can substitute lenses for the spherical mirrors, and a prism or transmission grating for the reflection grating. The results produce monochromators that look different but still operate essentially the same way. We will examine two of these not-so-different monochromators.

A TRANSMISSION GRATING SPECTROPHOTOMETER

The optics of a monochromator using a transmission grating are quite simple. Lenses are often used in place of spherical mirrors because the lenses can be placed very close to the transmission grating. This design is utilized in the inexpensive commercial unit illustrated below. The optical diagram is for the Coleman Junior Spectrophotometer.



A TRANSMISSION GRATING spectrophotometer which moves the source in order to scan the spectrum across the exit slit.

AN OPTIONAL EXPERIMENT....

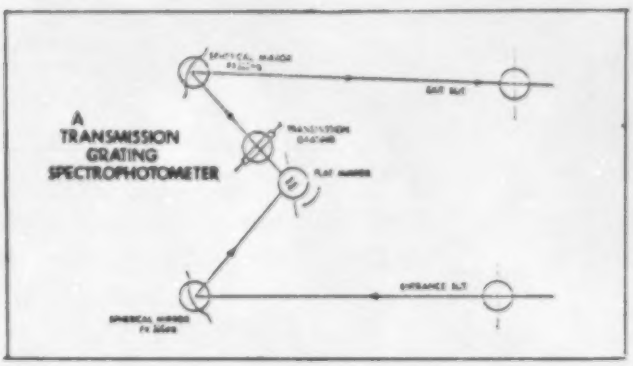
....BUILDING A TRANSMISSION GRATING SPECTROPHOTOMETER

The purpose of this experiment is to assemble and evaluate a spectrophotometer using a transmission grating.

The spectrophotometer you set up in the laboratory does not use lenses. It happens that it is easier to use spherical mirrors. If you are inventive, you might search for a way of using lenses with the transmission grating.

PROCEDURE

1. *Place the optical components* on the layout provided.
2. *Align the components.* Use the suggestion in the text on page 56.
3. *Follow the data collection* procedures on page 59 used in the previous laboratory.
4. *Follow the calibration procedures* on page 60.



THE LAYOUT for an experiment using a transmission grating in a spectrophotometer. Unlike the commercial unit on the opposite page, this layout uses a rotating mirror to scan the spectrum over the exit slit.

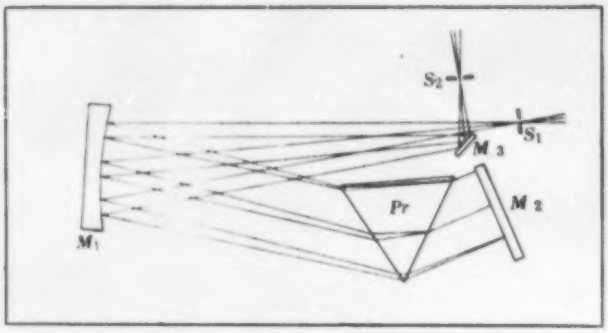
A PRISM SPECTROPHOTOMETER

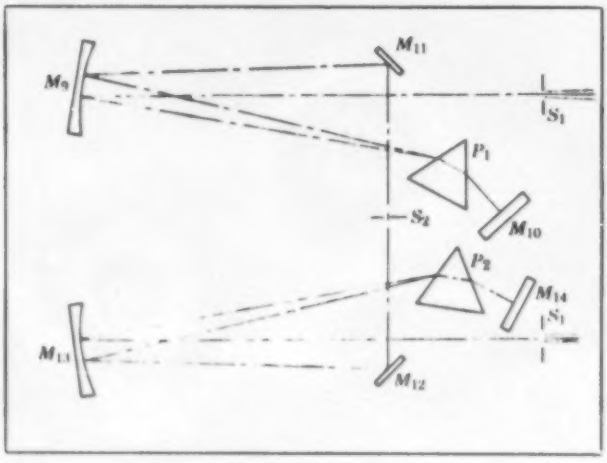
INTRODUCTION

One of the shortcomings of prisms is their low dispersion over most of the spectrum. The dispersion can be doubled by passing light through the prism twice. This is accomplished by placing a mirror just in back of the prism. This arrangement is called the Littrow mount. It is illustrated below.

The Littrow mount is actually used in commercial spectrophotometers. The drawings below are diagrams of the monochromator in actual instruments. The lower instrument uses two Littrow mounts to improve dispersion even more.

The Littrow mount is difficult to set up on your student spectrophotometer because the exit beam is reflected back along the entrance beam. As a result the two slits must be quite close.





COMMERCIAL MONOCHROMATORS using the Littrow mount. The designers of the lower instrument liked the Littrow mount so much, they used it twice! In both diagrams, S_2 is the exit slit. But in the lower one, the light continues through a second, symmetric monochromator. This doubles the dispersion of each prism, thereby improving the resolution by a factor of two.

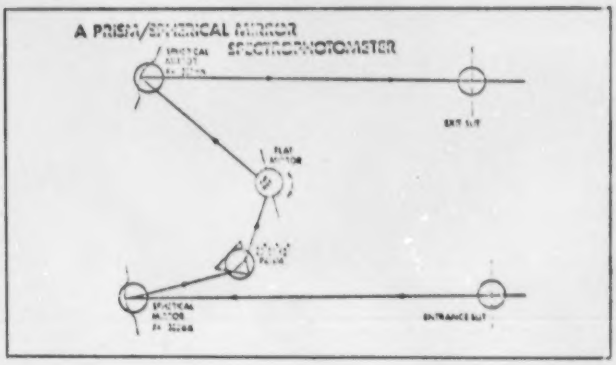
Let us follow the path of light through the upper monochromator. Light comes through slit S_1, and is rendered parallel by the spherical mirror, M_1. This parallel light passes through the prism, Pr; and is dispersed. The light reflects from the mirror M_2 and almost exactly retraces its path backwards. If this really happened, light would go back out the entrance slit. But by turning M_2 slightly, the light strikes M_3 instead and is reflected to the exit slit, S_2. Turning M_2 sweeps the spectrum across the exit slit.

AN OPTIONAL EXPERIMENT....
....BUILDING A PRISM SPECTROPHOTOMETER

In the laboratory we will be content to use a prism without reflecting the beam back through the prism for a second pass. This is not a Littrow mount. The layout we use is reproduced below. Two different systems are shown, one using lenses and one using spherical mirrors to collimate and refocus the light. One interesting feature of these layouts is that they can be aligned easily. By removing the prism, P, and replacing it with a flat mirror, the lenses should focus a white image of the entrance slit onto the exit slit.

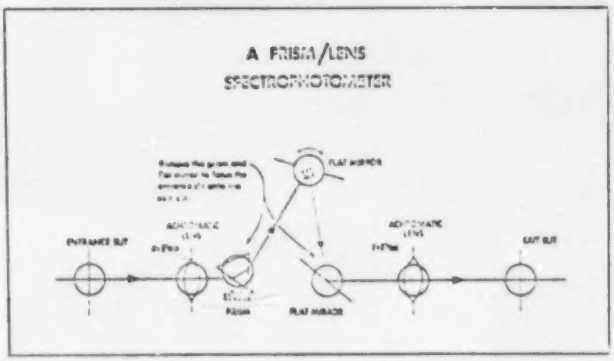
When you replace the prism, you may notice that the image of the spectrum is curved. This is always a problem with prism spectrophotometers. Since it cannot be solved easily, most designers use slightly curved slits. Unfortunately, we do not have curved slits, so we must take some loss in resolution.

As before the purpose of the laboratory will be to assemble and evaluate the spectrophotometer.



PROCEDURE

1. *Place the optical components* on the prism layout provided.
2. *Align the components.* Use the suggestion in the text on page 56.
3. *Follow the data collection* procedures on page 59 used in the previous laboratory.
4. *Follow the calibration procedures* on page 60.



TWO PRISM SPECTROPHOTOMETER layouts that can be used in the laboratory. Note that they do not use a Littrow mirror.

(OPTIONAL)

SPECTROPHOTOMETER SPEC'S

INTRODUCTION

Spec's (or specifications) give the details of the quality of instruments. It is often hard to understand spec sheets because of the jargon and special words they use. But now that you understand the principles behind the operation of monochromators, you should be able to figure out what they are saying. For example, look at the two spec sheets on these pages. You should do alright on some of the specifications but others need explanation. These explanations have been added to the sheets.

READABILITY vs ACCURACY: You may be able to read the dial to within 1 nm but that reading may not actually be the correct wavelength. This says it will be right to within 2.5 nm.

SPECTRAL SLIT WIDTH: The actual slit width is not 20 nm. Instead, its width is such that the *resolution* is 20 nm.

wavelength range	340-950 nm
wavelength accuracy	2.5 nm
wavelength readability	1 nm (1/5 division)
spectral slit width	20 nm nominal, constant over entire range
photometric accuracy (linearity)	±2.5 percent of full scale
photometric reproducibility	±1 percent of full scale
monochromator	reflectance grating, 600 grooves / mm
regulation	±1 percent T for line voltage change from 105-125 V, or 210-250 V with step-down transformer (transistorized model)
readout	meter, 9 cm mirrored scale calibrated in percent transmittance and 'absorbance' units
detectors	standard phototube 340-625 nm accessory phototube with red filter 625-950 nm accessory phototube with filter 380-715 nm

PHOTOMETRIC ACCURACY vs REPRODUCIBILITY: Never believe any meter. This spec says that if the output meter reads 50% transmission the actual transmission is probably somewhere between 47.5% and 52.5%A (ie 50 ± 2.5%). If you repeat the measurement you will get between 49% and 51%, but the accuracy is still only ± 2.5% of your best average measurement.

REGULATION: The voltage of household electricity often varies widely depending on the total area demand. This drastically affects the amount of light emitted by the source, which in turn affects the amount of light detected. Since these variations have nothing to do with the sample, they cause errors. All this is fixed by a voltage regulator which steadies the voltage supplied to the lamp. Here, a line voltage change from 105v to 125v would only cause a 1% error in measured transmission (T).

DETECTORS: Different detectors are required for different wavelength ranges. This tells which detector (and any additional filters) must be used for different wavelength regions.

RESOLVING POWER: The best resolution possible with the narrowest slit.

STRAY LIGHT: Sometimes light other than the desired color can get to the detector, causing errors, particularly when transmission is low.

The Monochromator unit consists of the optical system, mechanical drive, and electric motors that operate on signals from the electronic Control Unit.

Type of Mount	Single-pass Czerny-Turner mounting with folding mirrors to provide entrance and exit beams on a common optic axis.
Aperture Ratio	f/6.8 at 2000 angstroms.
Focal Length	350 millimeters.
Resolving Power	Better than 1 angstrom. Line-profile half-width less than 0.5 angstrom.
Stray Light	0.1% or less within ±1½ bandwidths of a given line.
Wavelength Range	Zero order to 10,000 angstroms, first order, with 1180 line/mm grating. Usable range with standard 1P28A detector, limited by air cutoff and detector sensitivity, is 1900 angstrom to 7000 angstrom. Lower limit may be extended to below 1800 angstrom by flushing the optical path with dry nitrogen . . . upper limit by use of other available detectors.
Wavelength Accuracy	Relative error ±1 angstrom throughout usable wavelength range.
Wavelength Resettability	±0.1 angstrom on the basis of resetting on the maximum of a narrow emission line, with photo-detected recorder output as indicator.
Reciprocal Dispersion	Approximately 20 angstrom/mm at exit slit with 1180 lines/mm grating.
Grating	Precision plane grating replica; 48 mm x 48 mm ruled area. Standard grating of 1180 lines/mm, blaze wavelength 2500 angstroms. (Gratings of other line spacing and blaze will be made available in the future.)
Mirrors	Aluminized first-surface mirrors with MgF_2 over coating. Optical surfaces corrected to 1/4-wave mercury green line.
Collimating and Focusing	50 mm diameter, parabolic, 350 mm focal length.
Folding	25 mm x 35 mm plane.
Slits	Ground and polished straight knife edges, bilaterally adjustable; entrance and exit slit-width ganged to single control.
Width	Continuously variable between 5 and 2000 microns. A 4-digit counter reads directly in microns.
Height	12 mm maximum; provision for intermediate heights of 0.5, 1, and 3 and 5 mm.
Wavelength-Scan Mechanism	Sine-bar and precision lead-screw assembly driven by precision stepping motor. A 5-digit counter reads directly in angstroms. Fractional scale of 0.2 angstrom divisions permits readability of 0.1 angstrom.

RECIPROCAL DISPERSION: This is dispersion as we have used the word. Moving the spectrum at the exit slit one millimeter changes the color getting through by 20A.

WIDTH: This instrument reads the actual slit widths.

BLAZE WAVELENGTH: The blaze improves the light intensity around one particular angle. This angle corresponds to 2500A here.

REVIEW

SUMMARY

In the preceeding chapter we have: examined the optical components of a spectrophotometer; assembled these components into an improved spectrophotometer; used this spectrophotometer to obtain transmission spectra of filters; and discussed how these ideas are used in practice.

The optical components discussed include lenses and spherical mirrors. Although lenses use refraction and spherical mirrors use reflection to bend the light, they both accomplish the same results. Both can collimate, or reader parallel, rays of light which are diverging from a point; and both can collect or focus parallel light at a point. This is their use in spectrophotometers since the dispersive elements require parallel rays of light for proper operation.

An experiment was performed with a spectrophotometer using spherical mirrors for optics and a diffraction grating for dispersion. Lenses and/or prisms could have been substituted. In order to find the transmission spectra for certain filters we had to accurately find the relationship between dial settings and wavelength - a process called *calibration*. A method to recalibrate a spectrophotometer after it has once been calibrated was discussed.

The experiment illustrated the uses and construction of commercial spectrophotometers. Just as they can be used to identify a filter, spectrophotometers can identify compounds - qualitative analysis. Spectrophotometers can also be used for quantitative analysis to determine the amounts of known chemicals presents. The specifications or specs of commercial spectrophotometers were discussed.

QUESTIONS

1. List five optical elements commonly found in spectrophotometers.

2. What is the function of each element listed in question #1.?

3. How does a lens work? What physical principle does it exploit? What other spectrophotometer optical element uses this principle?

4. Why are resolution and slit width related?

5. State four properties of the dispersive elements that are important in spectrophotometers.

6. Compare and contrast prisms and reflection gratings on their performance on the four properties stated in question #5. Relate this performance to the physical principles that each element utilizes in its operation.

PROBLEMS

1. Why are slits used in spectrophotometers instead of

   a) large holes b) small holes c) any other pattern such as a cross

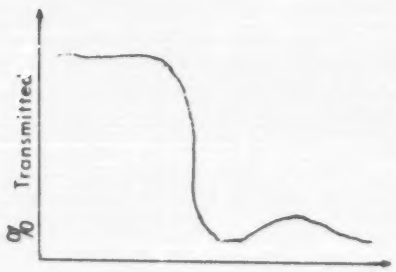
2. Is it possible to use a single transmission spectrum from a spectrophotometer for both qualitative and quantitative analysis at the same time? Explain your answer.

3. Where in the spectrophotometer path is the best place for the sample? Should it be before the first slit; just after it; near the exit slit; or somewhere else? Why?

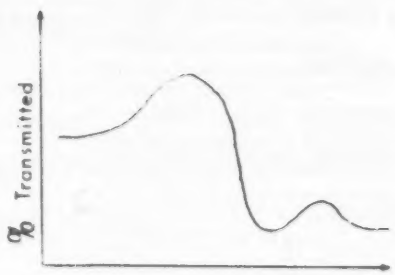
4. Set up a spectrophotometer using a prism and lenses. Measure your resolution and dispersion. Is there any sense in which this spectrophotometer is better or worse then the one you assembled before?

5. Suppose you were going to manufacture precision visible range spectrophotometers. What improvements would you desire to make in the student spectrophotometer before you would sell it commercially? How would you accomplish these improvements?

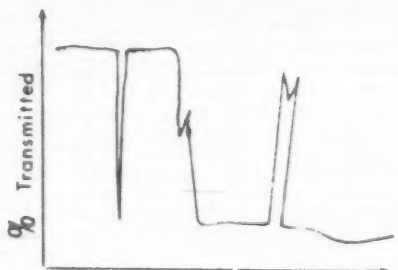
6. The unknown is most likely which of these substances? Explain the imperfect match.



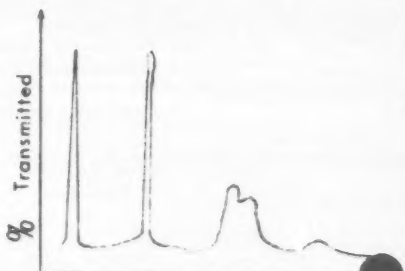
UNKNOWN



SUBSTANCE A



SUBSTANCE B



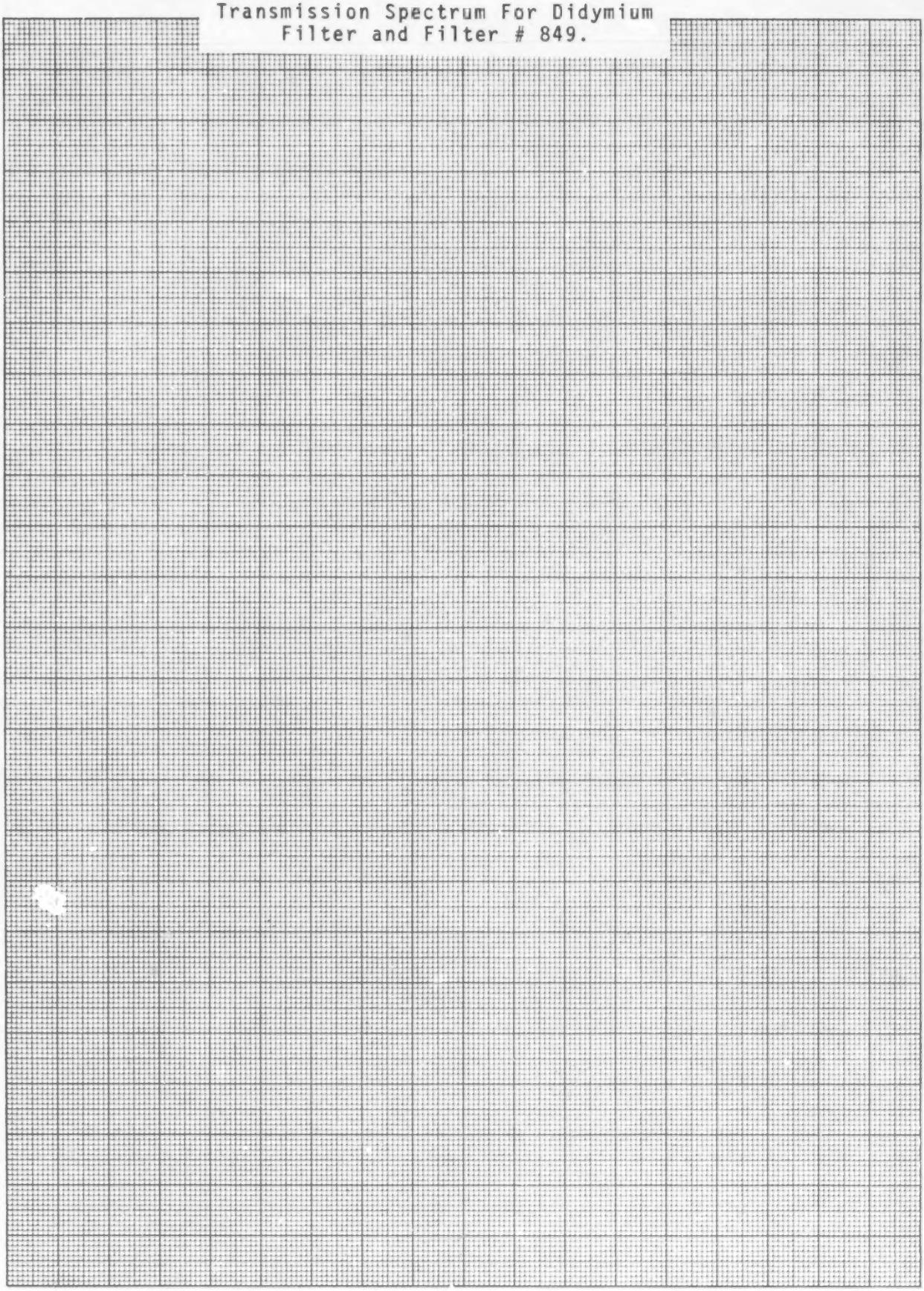
SUBSTANCE C

Table of % Transmission versus Color and Dial Reading for didymium filter & filter # 849.

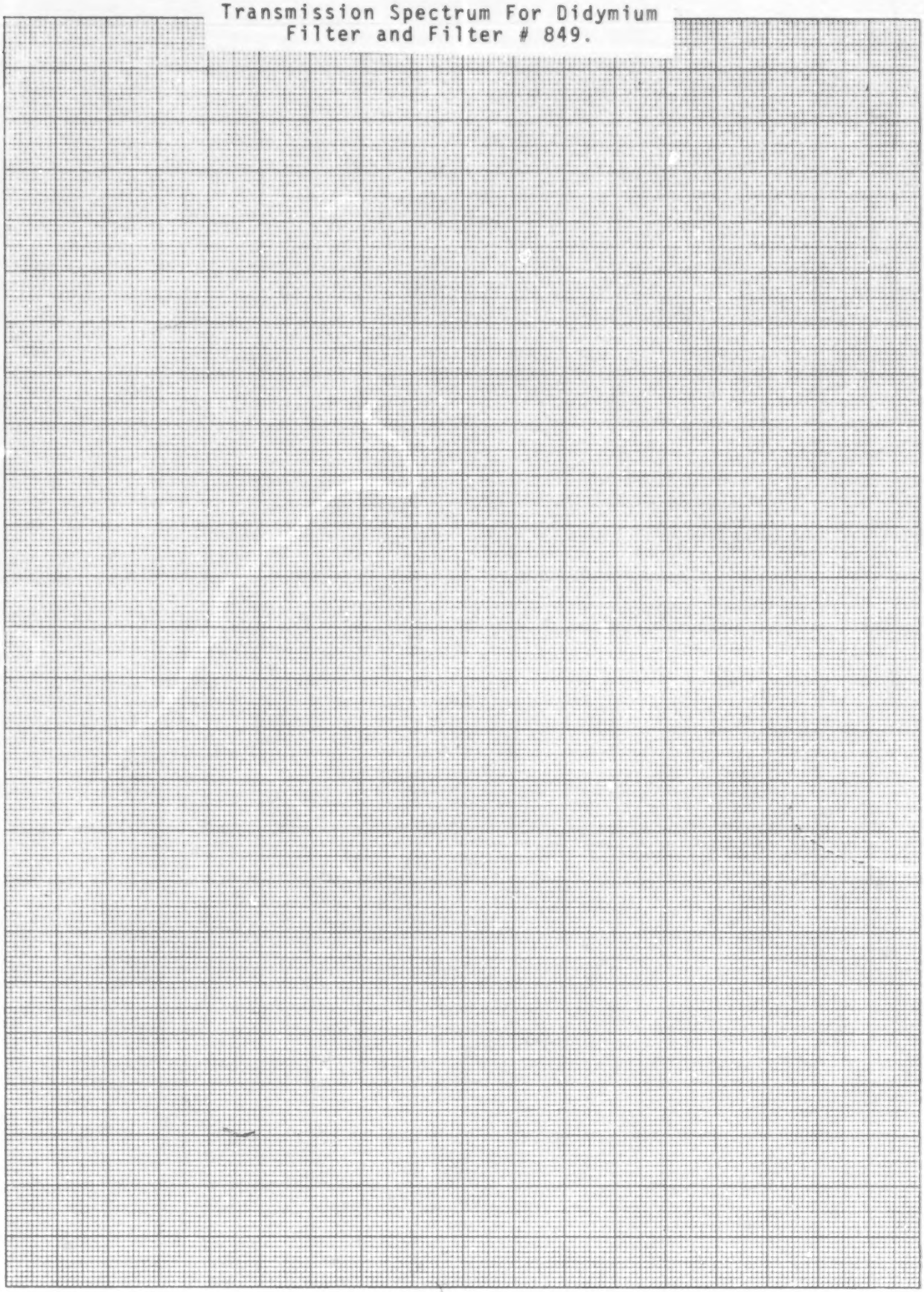
Table of Dial Reading versus Wavelength for key features of the didymium spectrum.

88

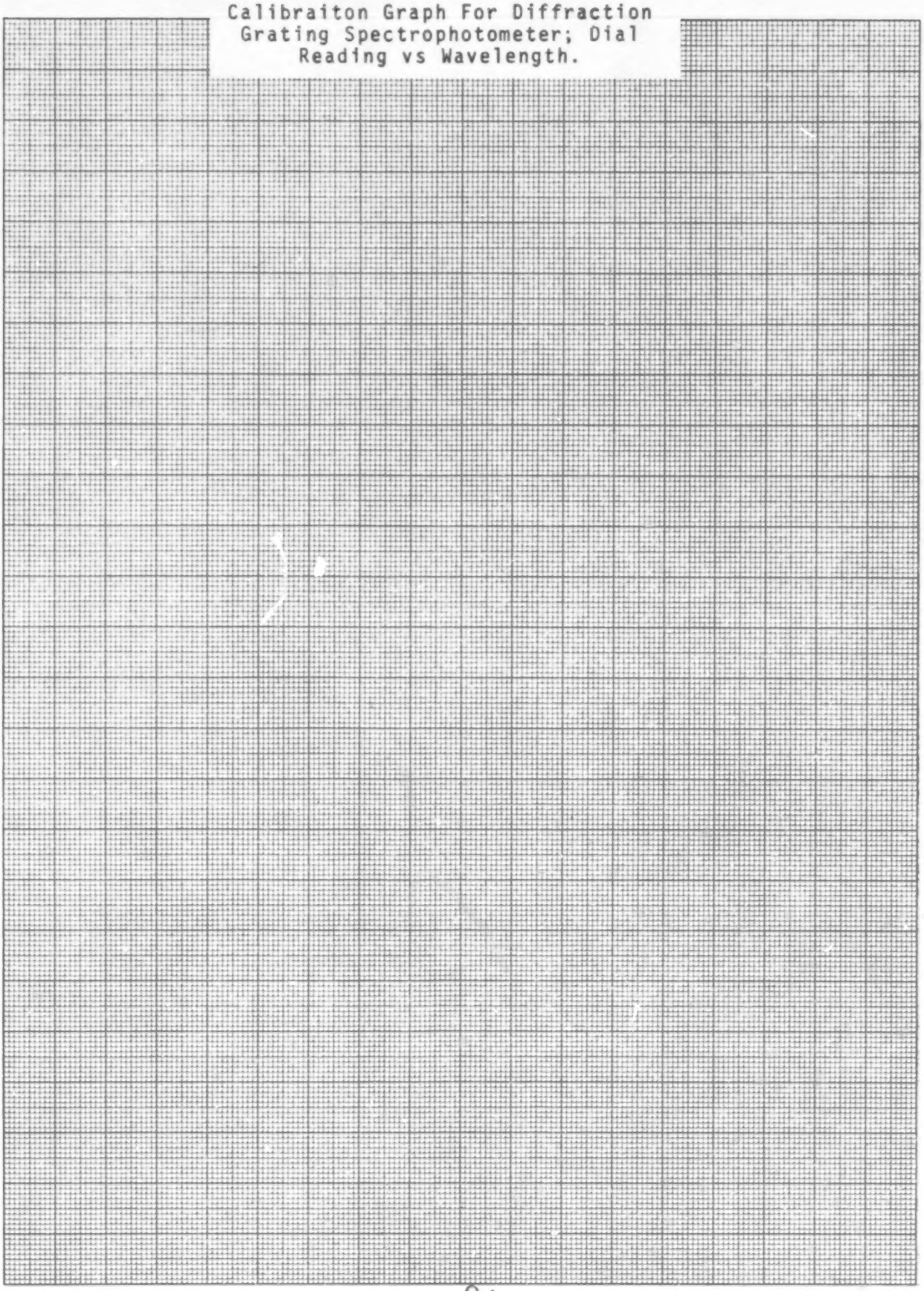
Transmission Spectrum For Didymium Filter and Filter # 849.



Transmission Spectrum For Didymium Filter and Filter # 849.



Calibraiton Graph For Diffraction Grating Spectrophotometer; Dial Reading vs Wavelength.



Calibration Graph For Diffraction Grating Spectrophotometer; Dial Reading vs Wavelength.

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